EXPERIMENTAL AND NUMERICAL STUDIES ON BEHAVIOUR OF FRP STRENGTHENED DEEP BEAMS WITH OPENINGS

A thesis

submitted by

HEMANTH KUMAR G

Roll no.210CE2024

In the partial fulfillment for
the award of the degree

of

MASTER OF TECHNOLOGY

DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA 769008

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Under the guidance of

DR. K. C. BISWAL

DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA 769008

May 2012

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ROURKELA – 769008, ORISSA
INDIA

This is to certify that the thesis entitled "**EXPERIMENTAL AND NUMERICAL STUDIES ON BEHAVIOUR OF FRP STRENGTHENED DEEP BEAMS WITH OPENINGS"** submitted by **Hemanth Kumar G** in partial fulfilment of the requirement for the award of **Master of Technology** degree in **Civil Engineering** with specialization in **Structural Engineering** to the National Institute of Technology, Rourkela is an authentic record of research work carried out by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Project Guide

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M.Tech Structures

ABSTRACT

Reinforced concrete deep beams are widely used as transfer girders in offshore structures and foundations, walls of bunkers and load bearing walls in buildings. The presence of web openings in such beams is frequently required to provide accessibility such as doors and windows or to accommodate essential services such as ventilating and air conditioning ducts. Enlargement of such openings due to architectural/mechanical requirements and/or a change in the building's function would reduce the element's shear capacity, thus rendering a severe safety hazard. Limited studies have been reported in the literature on the behavior and strength of RC deep beams with openings. When such enlargement is unavoidable adequate measures should be taken to strengthen the beam and counteract the strength reduction.

The present experimental investigation deals with the study of deep beams containing openings and the validation of results with FEM model using ANSYS. A total of 5 deep beams with openings are casted without shear reinforcements and are tested under three-point loading. Test specimen has a cross section of 150x460 mm and a total length of 1200 mm. Two circular openings, one in each shear span, are placed symmetrically about the mid-point of the beam. The structural response of RC deep beams with openings was primarily dependent on the degree of the interruption of the natural load path. Externally bonded GFRP shear strengthening around the openings was found very effective in upgrading the shear strength of RC deep beams. The strength gain caused by the GFRP sheets was in the range of 68–125%. Finite element modeling of RC deep beams containing openings strengthened with GFRP sheets is studied using ANSYS and the results are compared with experimental findings.

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ABBREVIATIONS

ACI	American Concrete Institute
CEB-FIP	Comité Euro-International du Béton- Fédération Internationale de la Précontrainte
CFRP	Carbon Fibre Reinforced Polymer
CIRIA	Construction Industry Research and Information Association
CSA	Canadian Standards Association
FE	Finite Element
FRP	Fibre Reinforced Polymer
GFRP	Glass Fibre Reinforced plastic
GRP	Glass Reinforced Plastic
HSC	High Strength Concrete
HSSCC	High Strength Self Compacting Concrete
HYSD	High Yield Strength Deformed
IS	Indian Standards
PSC	Portland Slag Cement
RC	Reinforced Concrete
SCC	Self Compacted Concrete
STM	Strut and Tie Model

NOTATIONS

ENGLISH

l	Effective span
D	Overall depth of the beam
L_d	Development length for the design stress in the reinforcement
t	Thickness of the beam
L	Overall length of the beam
f_{ck}	Characteristic cube compressive strength of concrete
M_u	Moment of resistance
d	Effective depth
z	Lever arm
A_{st}	Area of steel

CHAPTER-1

INTRODUCTION

1.1 DEEP BEAM

Beams with large depths in relation to spans are called deep beams. As per the Indian Standard, IS 456:2000, Clause 29, a simply-supported beam is classified as deep when the ratio of its effective span L to overall depth D is less than 2. Continuous beams are considered as deep when the ratio L/D is less than 2.5. The effective span is defined as the centre-to-centre distance between the supports or 1.15 times the clear span whichever is less. They are structural elements loaded as simple beams in which a significant amount of the load is carried to the supports by a compression force combining the load and the reaction.

As a result, the strain distribution is no longer considered linear, and the shear deformations become significant when compared to pure flexure. Because of their proportions deep beams are likely to have strength controlled by shear rather than flexure. On the other hand, their shear strength is expected to be significantly greater than predicted by the usual equations, because of a special capacity to redistribute internal forces before failure and to develop mechanisms of force transfer quite different from beams of common proportions (Winter and Nelson, 1987).Deep beams are widely used as transfer girders in offshore structures and foundations, walls of bunkers, load bearing walls in buildings, plate elements in folded plates, pile caps, raft beam wall of rectangular tank, hopper, floor diaphragm and shear walls.

With the strong growth of construction work in many developing countries, deep beam design and its behaviour prediction is a subject of considerable relevance. Traditional design assumptions, especially regarding plane section remaining plane after bending for shallow beams, do not apply to deep beams. Even the definition of transition from shallow to deep beam is imprecise in most codes of practice. The ACI 318-99 and CIRIA Guide 2 use span/depth ratio to define RC deep beams while the Canadian code CSA 1994 and CEB-FIP model code employs the concept of shear span/depth ratio. The ACI code defines beams with clear span to effective depth ratios less than 5 as deep beams, whereas CEB-FIP 1993 code treats simply supported and continuous beams having span/depth ratios less than 2 and 2.5 respectively, as deep beams. However it should be noted that the design of these structural elements are not adequately covered by existing codes of practices. Failure behaviour of deep beams is significantly different from that of shallow beams because of geometry and load transfer mechanism. Thus serviceability and failure pattern of these structural elements is not reported extensively due to the lack of clear procedure for prediction of their behaviour.

Fig. 1.1 Deep Beam without openings

1.2 DEEP BEAM WITH OPENINGS

In contrast to solid deep beams, there has been little work done with deep beams with openings. Large openings through structural members are frequently required for mechanical and electrical conduits or even for means of passageways, such as openings for doors and hallways in buildings. Openings in deep beams may be desired for such things as windows and doors, or for passage of utility lines and ventilation ducts. By allowing openings in deep beams for utilities to pass, there can be reduction in building storey height.

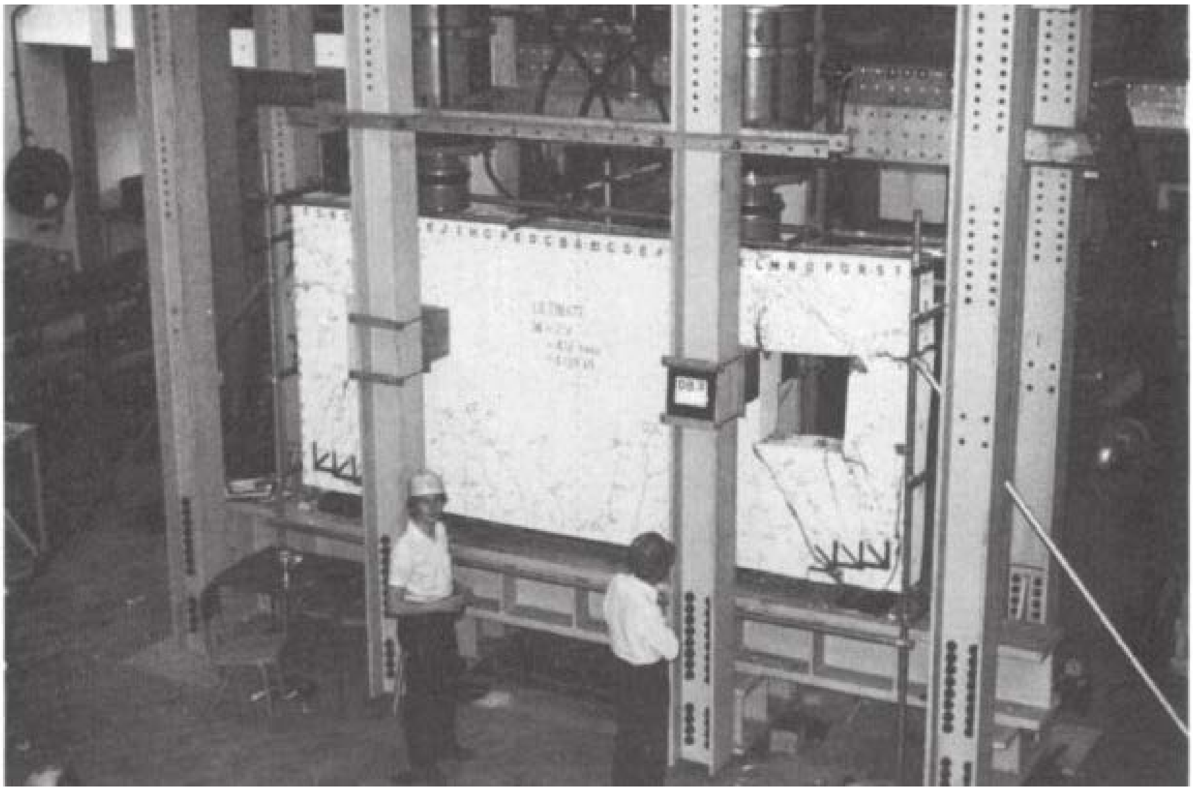


Fig. 1.2 Deep Beams with openings (Source: Google)

1.3 FIBRE REINFORCED POLYMER (FRP)

High strength non-metallic fibres, such as carbon, glass and aramid fibres, encapsulated in a polymer matrix in the form of wires, bars, strands or grids have shown great potentials as reinforcement for concrete, particularly where durability is of main concern. It is commonly known as fibre reinforced polymer or, in short, FRP. Despite being a recent development, numerous investigations have already been reported in the literature on various aspects of its structural use. Fibre-reinforced polymers (FRP) have been used for structural reinforcement materials and also for bridge construction materials such as bridge decks and materials. One area where FRP can play a major role is in strengthening and retrofitting of degraded or strength deficient structures already in existence. By virtue of its light-weight, extraordinarily high strength and high corrosion resistance, FRP presents an attractive material for structural rehabilitation. Moreover, being available in the form of thin sheets, such a system makes very little change to the dimension of the existing member.

1.4 ADVANTAGES OF FRP

FRP materials have higher ultimate strength and lower density as compared to steel. When these properties are taken together they lead to fibre composites having a strength/weight ratio higher than steel plate in some cases. The lower weight of FRP makes installation and handling significantly easier than steel. These properties are particularly important when installation is done in cramped locations. Other works like works on soffits of bridges and building floor slabs are carried out from man-access platforms rather than from full scaffolding. We all know that steel plate requires heavy lifting gear and are to be held in place while the adhesive gains its strength and bolts are fitted through the steel plate into the parent concrete to support the plate while the adhesive cures. On the other hand, the application of FRP plate or sheet material is like applying wallpaper; once it has been rolled on carefully to remove entrapped air and excess adhesive it may be left unsupported. Here, no bolts are required; in fact, the use of bolts would seriously weaken the material unless additional cover plates are bonded on. Furthermore, because there is no need to drill into the structure to fix bolts or other mechanical anchors there is no risk of damaging the existing reinforcement. Fibre composite materials are available in very long lengths while steel plate is generally limited to 6 m. The availability of long lengths and the flexibility of the material also simplify installation:

- Laps and joints are not required
- The material can take up irregularities in the shape of the concrete surface
- The material can follow a curved profile; steel plate would have to be pre-bent to the required radius.
- The material can be readily installed behind existing services
- Overlapping, required when strengthening in two directions, is not a problem because the material is thin.

The materials fibres and resins are durable if correctly specified, and require little maintenance. If they are damaged in service, it is relatively simple to repair them, by adding an additional layer. The use of fibre composites does not significantly increase the weight of the structure or the dimensions of the member. The latter may be particularly important for bridges and other structures with limited headroom and for tunnels.

In terms of environmental impact and sustainability, studies have shown that the energy required to produce FRP materials is less than that for conventional materials. Because of their light weight, the transport of FRP materials has minimal environmental impact. These various factors in combination lead to a significantly simpler and quicker strengthening process than when using steel plate. This is particularly important for bridges because of the high costs of lane closures and possession times on major highways and railway lines. It has been estimated that about 90% of the market for plate strengthening in Switzerland has been taken by carbon plate systems as a result of these factors.

1.5 DISADVANTAGES OF FRP

The main disadvantage of externally strengthening structures with fibre composite materials is the risk of fire, vandalism or accidental damage, unless the strengthening is protected. A particular concern for bridges over roads is the risk of soffit reinforcement being hit by over-height vehicles. A perceived disadvantage of using FRP for strengthening is the relatively high cost of the materials. However, comparisons should be made on the basis of the complete strengthening exercise; in certain cases the costs can be less than that of steel plate bonding. A disadvantage in the eyes of many clients will be the lack of experience of the techniques and suitably qualified staff to carry out the work. Finally, a significant disadvantage is the lack of accepted design standards.

1.6 IMPORTANCE OF STRENGTHENING

As infrastructures have aged, interest in the need for an effective means to rehabilitate concrete structures has increased. One of the most challenging tasks in this regard is to upgrade the overall capacity of the concrete structures in strength and ductility. Recently, composite materials have been widely employed to retrofit concrete structures due to their advantages in non-corrosiveness, high resistance to chemicals, high strength-to-weight ratio, and improved response in fatigue and damping. Concrete columns retrofitted by external steel jackets improved both the shear and bending responses of the members. Recently, fibre reinforced polymer (FRP) materials have been promoted as one of the most promising and economical alternatives for rehabilitating concrete structures. FRP materials are lighter, easier to assemble, and more durable than alternative repair systems. Several experiments have shown that concrete wrapped by glass or carbon FRP jackets improved the strength and ductility of the confined concrete. A great deal of research on CFRP retrofitted concrete systems has been conducted. The investigations of CFRP retrofit systems, however, have primarily focused on flexural and shear strengthening for slender concrete members. Limited work has been done on CFRP strengthened deep reinforced concrete RC members, in which the Bernoulli hypothesis is not applicable. Therefore, in current design guides such as the ACI code, CFRP strengthened slender members can be analyzed with some accuracy, while CFRP strengthened deep members are still being analyzed by approximate procedures that have been developed for slender members.

1.7 NEED FOR PRESENT WORK

Reinforced concrete (RC) deep beams have been used in high-rise buildings, offshore structures, transfer girders, some walls, and pile caps. The presence of web openings in such beams is frequently required to provide accessibility such as doors and windows or to accommodate essential services such as ventilating and air conditioning ducts. Enlargement of such openings due to architectural/mechanical requirements and/or a change in the building's function would reduce the element's shear capacity, thus rendering a severe safety hazard. Up to date, limited studies have been reported in the literature on the behaviour and strength of RC deep beams with openings. It was concluded that increasing the opening size would result in a significant reduction in the shear strength. When such enlargement is unavoidable adequate measures should be taken to strengthen the beam and counteract the strength reduction.

1.8 OBJECTIVE

The objective of this investigation is to study the shear behaviour of deep beams containing openings loaded up to failure and to study the effects and enhancement of strength in deep beams containing openings when strengthened externally by FRP.

1.9 ORGANIZATION OF THESIS

This introductory chapter (Chapter 1) gives a brief introduction to the concept of deep beam and deep beam with openings and its uses. The importance of fibre reinforced polymer in strengthening of degraded concrete structures and the advantages and disadvantages of FRP the need for present work and also the objective of the project is presented in this chapter.

Review of literature on deep beams and its behaviour with and without openings along with the, scope and methodology of the proposed work have been presented in Chapter 2.

Chapter 3 deals with the design stipulations of deep beam in general. An example with detailed reinforcement diagrams is also explained in this chapter.

Chapter 4 presents the detailed experimental study. Testing of all the beams with different FRP systems is also been covered in this chapter.

Finite element modelling of deep beam with openings using ANSYS have been presented in chapter 5.

Chapter 6 deals with the results and discussions which cover different failure modes observed, load deflection analysis and ultimate load carrying capacity of all the beams.

Chapter 7 deals with the conclusions and the scope for the future work.

CHAPTER-2

REVIEW OF LITERATURE

2.1 OVERVIEW

Limited studies have been reported in the literature on the behaviour and strength of deep beams and deep beams with openings [21]-[42], a fairly common structural element in tall buildings, offshore structures and in foundations systems. A. K. Sachan [21] performed an experimental study on "Behaviour of Fibre Reinforced Concrete Deep Beams", a total of 14 concrete deep beams were tested to failure and the effects of fibre content, percentage reinforcement and the type of loading were studied. It was found that the addition of steel fibres to concrete results in a significant increase in ultimate strength of deep beams. It was also observed that the failure of fibre reinforced concrete beams was more ductile and gradual compared with the failure of plain and reinforced concrete beams.

H. K. Lee [24] worked on "Behaviour and Performance of RC T-Section Deep Beams Externally Strengthened in Shear with CFRP sheets". In the paper a series of experimental tests were carried out to investigate the behaviour and performance of reinforced concrete (RC) T-section deep beams strengthened in shear with CFRP sheets. A total of 14 RC T-section deep beams were designed to be deficient in shear with a shear span-to-effective depth ratio (a/ d) of 1.22. Crack patterns and behaviour of the tested deep beams were observed during four-point loading tests. It was concluded from the test results that the key variables of strengthening length, fibre direction combination, and anchorage have significant influence on the shear performance of strengthened deep beams. In addition, a series of comparative studies between the present experimental data and theoretical results in accordance with the commonly applied design codes were made to evaluate the shear strength of a control beam and deep beams strengthened with CFRP sheets.

H. S. Kim [25] worked on “Structural Behaviours of Deep RC Beams under Combined Axial and Bending Force”. The paper presents experimental studies of deep reinforced concrete (RC) beam behaviours under combined axial and bending loads. In order to investigate the effect of axial loads on the structural behaviours of the deep RC beams, specimens were prepared to have different shear span-to-depth ratios and subjected to axial loads of 235kN or 470kN. From the experiments, structural behaviours such as failure modes, load-deflection relationships, and strains of steel bar and concrete are observed. As results, for the deep beam with shear span-to-depth ratio of 0.5, load at the beam failure decreases as applied axial load increases, while the deep beams with shear span-to-depth ratios of 1.0 and 1.5 shows that the applied axial load delays the beam failure. In addition, failure mode of the deep beam changes from shear failure to concrete crushing due to compressive stress at the top corners of RC beams as shear span-to-depth ratio decreases. From the experiments, it is important to notice that deep beam with relatively small span-to-depth ratio under axial load shows early failure due to concrete crushing, which cannot be directly applied to widely known design method for deep beam, strut-to-tie model.

Keun-Hyeok Yang [26] worked on “Shear Characteristics of High Strength Concrete Deep Beams without Shear Reinforcements”. A total of 21 beam specimens were tested to investigate their shear characteristics with the variables of concrete strength, shear span/depth ratio, and overall depth. Experimental results showed that the decrease in shear span/depth ratio and the increase in overall depth under the same shear span/depth ratio led to more brittle failure with wide diagonal cracks and high energy release rate related to size effects. The high-strength concrete deep beams exhibited more remarkable size effects with regard to brittle behaviour.

M. R. Islam [27] studied on “Shear Strengthening of RC Deep Beams using Externally Bonded FRP systems”. Six concrete deep beams were fabricated and tested to failure. One of the beams was tested in its initial condition to serve as reference, while the remaining five beams were tested after being strengthened using carbon fibre wrap, strip and grids. Tests have shown that the use of a bonded FRP system leads to a much slower growth of the critical diagonal cracks and enhances the load carrying capacity of the beam to a level quite sufficient to meet most of the practical upgrading requirements.

Abdur Rashid [28] studied on “Behaviour of Reinforced Concrete Deep Beam under Uniform Loading”, a total of 14 concrete deep beams were tested under four point loading condition simulating approximately the uniform distributed load. The test beams were simply supported and were made with brick aggregate concrete. The test beams were divided into two series in which first beam of each series was designed and detailed as per recommendations of the ACI Building Code 318-89 (ACI, 1989). In the remaining six beams of each series, the amount of either the flexural reinforcement or, the horizontal web reinforcement or, both were increased in relation to that of first beam of the corresponding series. Results shown that the diagonal crack develops first in relatively deeper beams and flexural cracks develop first in the shallower beams provided the beams have sufficient reinforcements.

Mohd. Zamin [29] studied on “Failure Modes and Serviceability of High Strength Self Compacting Concrete Deep Beams”. The main purpose of the study was to facilitate the prediction of deep beam failure related to tensile bar and web reinforcement percentage variations. Six high strength self-compacting concrete (HSSCC) deep beams were tested until failure. Strains were measured on concrete surface along mid span, tensile bar and compression strut trajectory. The load was incrementally applied and at each load increment new cracks, their widths and propagation were monitored. The results clearly showed that, at ultimate limit condition, the strain distribution on concrete surface along mid-span is no longer parabolic. In deep beams several neutral axes were obtained before ultimate failure is reached. As the load increased, the number of neutral axis decreased and at failure load it reduced to one. The failure of deep beams with longitudinal tensile steel reinforcement less than that suggested by ACI codes is flexural and is accompanied by large deflections without any inclined cracks. As the longitudinal tensile steel reinforcement increased, the failure due to crushing of concrete at nodal zones was clearly observed. The first flexural crack at mid-span region was always vertical. It appeared at 25-42% of peak load. The crack length was in the range of 0.24-0.6 times the height of section. As the tensile bar percentage increases number of cracks increases with reduced crack length and crack width.

Mohd. Zamin [30] studied on “An Experimental Investigation of the Stress-Strain Distribution in High Strength Concrete Deep Beams”. The paper discusses the behaviour, design and analysis of high strength reinforced concrete (HSC) deep beams regarding the neutral axis variation. Six(HSC)deep beams designed and casted with self-compacted concrete (SCC). The paper deals with the study of the stress-strain distribution along the beam section at mid-span and the variation of the neutral axis within the depth. Strain gauges were been attached on the concrete surface, on the tensile reinforcement and on the horizontal and vertical web bars to monitor the strains, both in concrete and in the different reinforcement bars. The data show clearly that the distribution of strains, and hence of stresses, in the deep beams studied is completely different from the linear one, commonly accepted for ordinary beams.

They also have more than one neutral axis, making the ordinary beam theory used in flexural design not justified in deep beams.

Sangdon Park [35] worked on “Strut-and-Tie Method (STM) for CFRP Strengthened Deep RC Members”. STM was used for the analysis of CFRP strengthened deep reinforced concrete members since a bonded CFRP element acts as an addition tension tie. A practical analysis and design process for CFRP strengthened deep RC members using the STM was presented in the paper. In addition, seven effective factor models accounting for reduction of strength in cracked concrete were also investigated. A total of 17 experimental deep beam test results were compared with the proposed STM approach results. It has been shown that the proposed STM approach with an effective factor model depending on the strut angle provides the best agreement with the test results.

T. M. Roberts [37] worked on “Shear Failure of Deep Fibre Reinforced Concrete Beams”. Totally nine deep, steel fibre reinforced concrete beams were tested to investigate the influence of fibres on the shear failure of deep beams. Only one type of fibre ’Duoform’ brass coated fibre, 0.38mm diameter by 38mm long was used in test programme. Results confirmed that the steel fibres can prevent shear failure in deep beams.

Tamer El Maaddawy and Sayed Sherif [38] worked on “FRP composites for shear strengthening of reinforced concrete deep beams with openings” The paper presents the results of a research work aimed at examining the potential use of externally bonded carbon fibre reinforced polymer (CFRP) composite sheets as a strengthening solution to upgrade reinforced concrete (RC) deep beams with openings. A total of 13 deep beams with openings were constructed and tested under four-point bending. Test specimen had a cross section of 80 x 500 mm and a total length of 1200 mm.

Two square openings, one in each shear span, were placed symmetrically about the mid-point of the beam. Test parameters included the opening size, location, and the presence of the CFRP sheets. The structural response of RC deep beams with openings was primarily dependent on the degree of the interruption of the natural load path. Externally bonded CFRP shear strengthening around the openings was found very effective in upgrading the shear strength of RC deep beams. The strength gain caused by the CFRP sheets was in the range of 35–73%. A method of analysis for shear strength prediction of RC deep beams containing openings strengthened with CFRP sheets was studied and examined against test results.

Wen-Yao Lu [40] studied on “Shear Strength prediction for Steel Reinforced Concrete Deep Beams”. In the paper the study on analytical method for determining the shear strengths of steel reinforced concrete deep beams under the failure mode of concrete crushing originally based on the softened strut-and-tie modal was carried out. By comparing the predictions of the proposed method with the available test results from the literature, it was found that the proposed method is capable of predicting the shear strengths for steel reinforced concrete deep beams with sufficient accuracy.

2.2 CRITICAL OBSERVATIONS

The following critical observations are made from the existing literature in the area of reinforced concrete deep beams and deep beams with openings.

- Most of the reported works are limited to deep beams.
- Limited work is done in deep beams with openings.
- Very fewer studies reported in deep beams without shear reinforcements.

2.3 SCOPE OF PRESENT WORK

In the present work it is proposed to study the behaviour of shear deficient reinforced concrete deep beams containing circular openings. All the beams are strengthened using externally bonded GFRP except one beam which serves as the control beam.. The beams are tested to failure by applying three point loading to evaluate the enhancement of shear strength due to strengthening of beams with GFRP. Finite element modelling of RC deep beams containing openings strengthened with GFRP sheets is studied using ANSYS and the results are compared with experimental findings.

2.4 METHODOLOGY

The methodology worked out to achieve the above-mentioned objectives is as follows:

(i) Review the existing literature and Indian design code provision for designing the deep beam.

(ii) Adopting a mix design of M15 grade concrete (as per IS 10262-2009) to construct the deep beam with circular openings.

(iii) A total of 5 beams were casted along with 3 cubes each for a beam.

(iv) All the beams were tested under single point loading after 28 days curing and even the cubes to determine the compressive strength of concrete.

(v) One beam was tested in its initial condition and remaining 4 beams were strengthened using glass fibre with different orientations and with increasing layers to determine the maximum strength condition.

(vi) All the beams are modeled in ANSYS by considering linear analysis and are compared with experimental models.

(vii) Results and discussions.

CHAPTER-3

DESIGN OF DEEP BEAM

3.1 INTRODUCTION

This chapter deals with the design criteria of deep beams. The following are the criterion to design a deep beam as per Indian Standard code (IS 456:2000)

3.1.1 Definition

As per clause 29.1; A beam shall be deemed to be a deep beam whenthe ratio of effective span to overall depth, (l/D)is less than:

1) 2.0 for a simply supported beam; and

2) 2.5 for a continuous beam.

3.1.2 Lever Arm

As per clause 29.2; The lever arm z for a deep beam shall be determined asbelow:

a) For simply supported beams:

$$\begin{cases} z = 0.2(l + 2D) & when\ \ 1 \le l/D \le 2 \\ z = 0.6l & when\ l/D < 1 \end{cases} \tag{3.1a}$$

b) For continuous beams:

$$\begin{cases} z = 0.2(l + 1.5D) & when\ \ 1 \le l/D \le 2.5 \\ z = 0.5l & when\ l/D < 1 \end{cases} \tag{3.1b}$$

Where *l* is the effective span taken as centre to centre distance between supports or 1.15 times the clear span, whichever is smaller, and *D* is the overall depth.

3.1.3 Reinforcement

As per clause 29.3.1, positive reinforcement is, the tensile reinforcement required to resist positive bending moment in any span of a deep beam shall:

a) extend without curtailment between supports;

b) be embedded beyond the face of each support, so that at the face of the support it shall have a development length not less than 0.8 L_d where L_d is the development length for the design stress in the reinforcement; and

c) be placed within a zone of depth equal to $0.25D – 0.05l$ adjacent to the tension face of the beam where *D* is the overall depth and *l* is the effective span.

As per clause 29.3.2, negative reinforcement is

a) Termination of reinforcement- For tensile reinforcement required to resist negative bending moment over a support of a deep beam:

   i) It shall be permissible to terminate not more than half of the reinforcement at a distance of 0.5 *D* from the face of the support where *D* is as defined in clause 29.2 of IS 456:2000; and

   ii) The remainder shall extend over the full span.

b) Distribution- When the ratio of clear span to overall depth is in the range 1.0 to 2.5, tensile reinforcement over a support of a deep beam shall be placed in two zones comprising:

   i) a zone of depth 0.2 *D*, adjacent to the tension face, which shall contain a proportion of the steel given by

$$0.5\left(\frac{l}{D} - 0.5\right) \tag{3.2}$$

   Where *l* is the clear span
   and *D* is the overall depth

ii) a zone measuring 0.3 *D* on either side of the mid-depth of the beam, which shall contain the remainder of the tension steel, evenly distributed. For span to depth ratios less than unity, the steel shall be evenly distributed over a depth of 0.8 *D* measured from the tension face.

3.2 MINIMUM THICKNESS

The minimum thickness of deep beams should be based on two considerations. First, it should be thick enough to prevent buckling with respect to its span and also its height. The empirical requirement to prevent bulking can be expressed as follows:

$$D/b<25 \text{ and } L/b<50$$

Where ‘b’ is thickness of the beam. Second, the thickness should be such that the concrete itself should be able to carry a good amount of the shear force that acts in the beam without the assistance of any steel.

3.3 STEPS OF DESIGNING DEEP BEAMS

The important steps in the design of R.C. deep beams are the following:

1) Determine whether the given beam is deep according to the definition.
2) Check its thickness with respect to buckling as well as its capacity to carry the major part of the shear force by the concrete itself.
3) Design for flexure.
4) Design for the minimum web steel and its distribution in the beam.
5) Design for the shear, if the web steel already provided is inadequate, design additional steel for shear requirements
6) Check safety of supports and loading points for local failure.

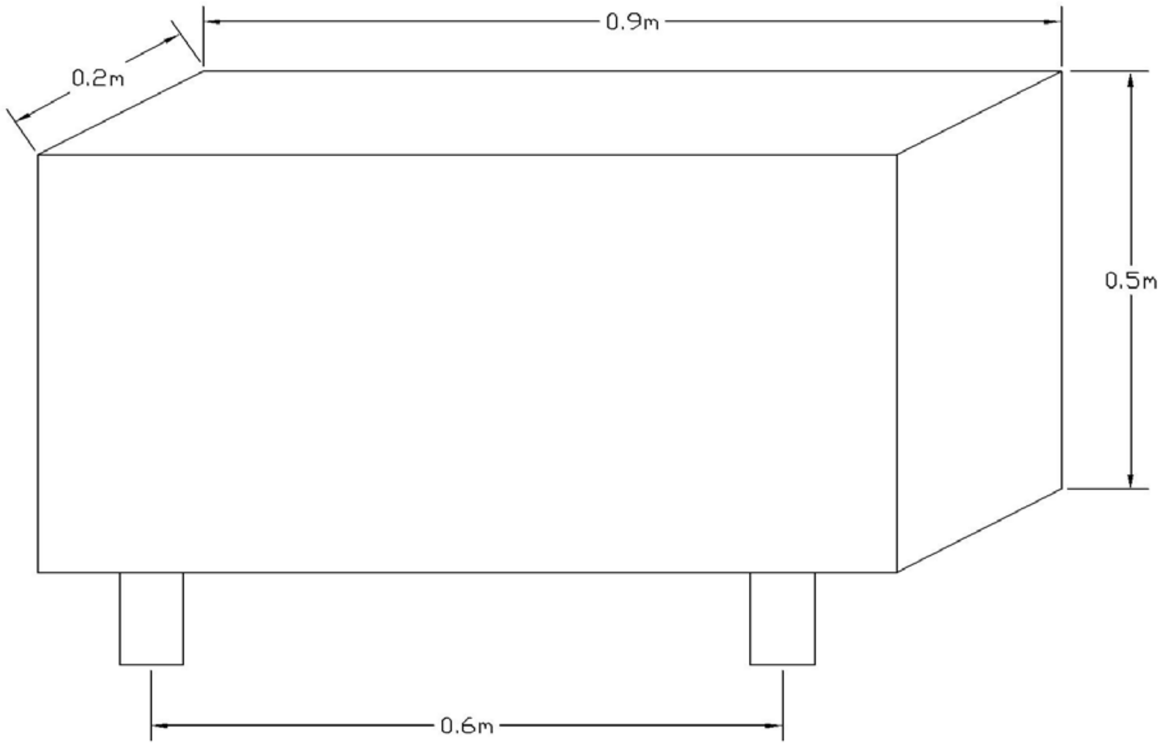
7) If the beams are not top loaded design the special features required for deep beam action under the special loading conditions.

8) Detail the reinforcements according to accepted practice.

3.4 DESIGN EXAMPLE

Overall Depth (D) = 0.5m

Width (b) = 0.2m



Overall Length (L) = 0.9m

Effective Span (l) = 0.6m

Clear cover = 25mm

Diameter of steel rods = 16mm

Effective Depth (d) = D-25-(16÷2)

= 500-25-8

= 467mm

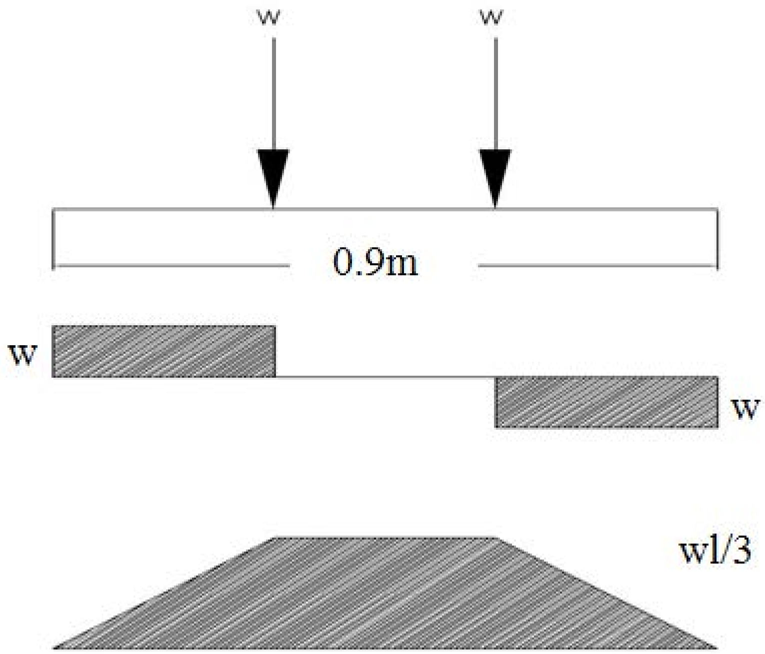


Fig. 3.1 SFD and BMD of the shown beam

Providing concrete grade M_{20} and Fe 415

f_{ck}= 20 N/mm^2

Considering a balance section

Moment of resistance (M_u) = 0.138 $f_{ck}bd^2$

= 0.138×20×200×467^2

= 120.38 KN m

Equating bending moment = Moment of resistance

Wl/3 = 120.38

W=601.9 KN

(i) Calculation of lever arm

For simply supported beam

z = 0.2(l+2D)
= 0.2(0.6+2(0.5))
= 0.32m

Moment of resistance with respect to compression in concrete

$0.87\ f_y A_{st}\ z = M_u$

$0.87 \times 415 \times A_{st} \times 320 = 120.38 \times 10^6$

$A_{st} = 1041.92\ mm^2$

(ii) Calculation of zone of depth

Zone of depth = 0.25D-0.05l
= (0.25×0.5-0.05×0.6)
= (0.125-0.03)
= 0.095m

Provide 6 bars of 16mm diameter @ 0.095m from soffit

(iii) Calculation of minimum horizontal reinforcement

Minimum horizontal reinforcement = 0.002×gross concrete area

= 0.002×200×1000

= $400mm^2$

⇨ $200mm^2$on both the sides

Provide 3 bars of 6mm diameter on both the faces @ 120mm c/c

(iv) Calculation of minimum vertical reinforcement

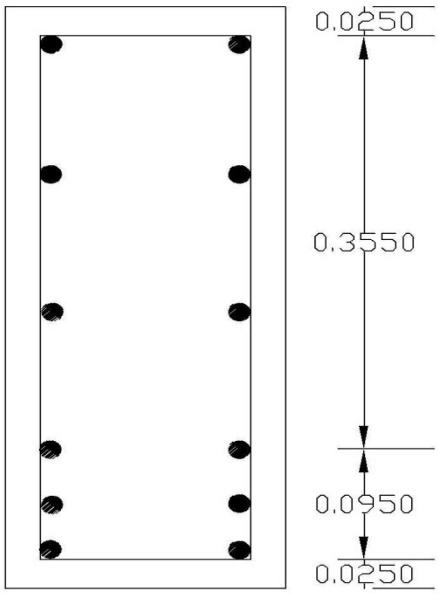
Minimum vertical reinforcement = 0.0012×gross concrete area

= 0.0012×200×1000

= $240mm^2$

⇨ $120mm^2$on both the sides

Provide 5 number of stirrups of 6mm diameter @ 180mm c/c



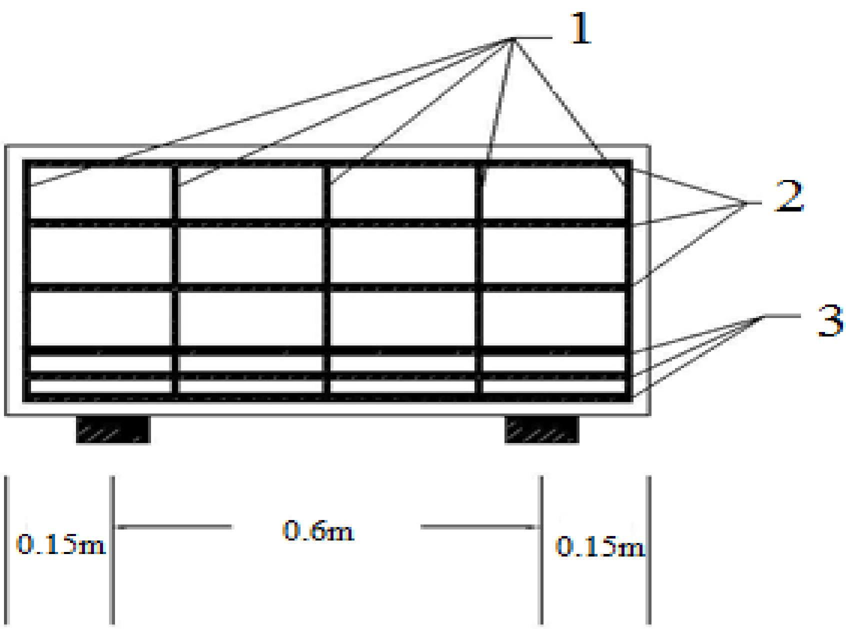


Fig. 3.2 Reinforcement detailing

1) 5 no.of stirrups of 6mm diameter @ 180mm c/c.
2) 6 no.of 6mm diameter bars @ 120mm c/c.
3) 6 no.of 16mm diameter bars spaced equally @ 0.095m from soffit.

CHAPTER-4

EXPERIMENTAL STUDY

4.1 CASTING OF BEAMS.

4.1.1 Beam Dimensions.

As per clause 29 of IS 456:2000 the beam dimensions were finalised as follows:

Length (L) = 1.2 m

Width (b) = 0.15 m

Depth (D) = 0.46 m

Effective span (l) = 0.9 m

It has been tested after 28 days with three point loading.

4.1.2 Casting of specimen.

For conducting experiment, the proportion of 1: 2: 4 is taken for cement, fine aggregate and course aggregate. The mixing is done by using concrete mixture. The beam is cured for 28 days. Three cubes are casted and are tested after 28 days to determine the compressive strength of concrete for 28 days.

4.1.3 Materials for casting.

- **Cement**

Portland Slag Cement (PSC) (Konark Cement) is used for the experiment. It is tested for its physical properties in accordance with Indian Standard specifications. It is having a specific gravity of 2.96.

- **Fine aggregate.**

  The fine aggregate passing through 4.75 mm sieve and having a specific gravity of 2.67 are used. The grading zone of fine aggregate is zone III as per Indian Standard specifications.

- **Coarse aggregate.**

  The coarse aggregates of two grades are used one retained on 10 mm size sieve and another grade contained aggregates retained on 20 mm sieve. It is having a specific gravity of 2.72.

- **Water.**

  Ordinary tap water is used for concrete mixing in all the mix.

4.1.4 Concrete properties.

a) Concrete grade = M15

b) Characteristics strength = 15 N/mm^2

c) Degree of quality control = Good

d) Degree of exposure = Mild

4.2 REINFORCEMENT DETAILING

High-Yield Strength Deformed bars of 12 mm and 8 mm diameter are used for the longitudinal reinforcement and 6 mm diameter bars are used as stirrups. The tension reinforcement consists of 2 no’s 12 mm diameter HYSD bars. Two bars of 8 mm of HYSD bars are also provided as hang up bars .The detailing of reinforcement of the beam is shown in figure 4.1(a) and 4.1(b).

Fig. 4.1(a) Reinforcement cage

Fig. 4.1(b) Reinforcement cage

4.3 GLASS FIBRES

Fibreglass (or glassfibre) (also called glass-reinforced plastic, GRP, glass-fibre reinforced plastic, or GFRP), is a fibre reinforced polymer made of a plastic matrix reinforced by fine fibres of glass. Fibreglass is a lightweight, extremely strong, and robust material. The glass fibres are divided into three classes: E-glass, S-glass and C-glass. The E-glass is designated for electrical use and the S-glass for high strength. The C-glass is for high corrosion resistance, and it is uncommon for civil engineering application. Of the three fibres, the E-glass is the most common reinforcement material used in civil structures.

Although strength properties of glass fibres are somewhat lower than carbon fibre and it is less stiff, the material is typically far less brittle, and the raw materials are much less expensive. Its bulk strength and weight properties are also very favourable when compared to metals, and it can be easily formed using moulding processes. The plastic matrix may be epoxy, a thermosetting plastic (most often polyester or vinyl ester) or thermoplastic. Common uses of fibreglass include boats, automobiles, baths, hot tubs, water tanks, roofing, pipes, cladding, casts and external door skins.

Table 4.1 Properties of Glass Fibres

Typical Properties	E-Glass	S-Glass
Density (g/cm^3)	2.60	2.50
Young's Modulus (GPa)	72	87
Tensile Strength (GPa)	1.72	2.53
Tensile Elongation (%)	2.4	2.9

4.4 FORM WORK

Form work is the term given to either temporary or permanent moulds into which concrete or similar materials are poured. The form work for the deep beam that is used to carry out the present project is as shown in Fig. 4.2

Fig.4.2 Deep beam frame

4.5 MIXING, COMPACTION AND CURING OF CONCRETE

Mixing of concrete is done thoroughly with the help of machine mixer so that a uniform quality of concrete is obtained. Compaction is done with the help of needle vibrator in all the specimens and care is taken to avoid displacement of the reinforcement cage inside the form work. Then the surface of the concrete is levelled and smoothened by metal trowel and wooden float. Curing is done to prevent the loss of water which is essential for the process of hydration and hence for hardening. It also prevents the exposure of concrete to a hot atmosphere and to drying winds which may lead to quick drying out of moisture in the concrete and there by subject it to contraction stresses at a stage when the concrete would not be strong enough to resists them. Here curing is done by spraying water on the jute bags spread over the surface for a period of 14 days.

4.6 STRENGTHENING OF BEAMS

At the time of bonding of fibre, the concrete surface is made rough using a coarse sand paper texture and then cleaned with an air blower to remove all dirt and debris. After that the epoxy resin is mixed in accordance with manufacturer's instructions. The mixing is carried out in a plastic container (100 parts by weight of Araldite LY 556 to 10 parts by weight of Hardener HY 951). After their uniform mixing, the fabrics are cut according to the size then the epoxy resin is applied to the concrete surface. Then the GFRP sheet is placed on top of epoxy resin coating and the resin is squeezed through the roving of the fabric with the roller .Air bubbles entrapped at the epoxy/concrete or epoxy/fabric interface are eliminated.

During hardening of the epoxy, a constant uniform pressure is applied on the composite fabric surface in order to extrude the excess epoxy resin and to ensure good contact between the epoxy, the concrete and the fabric. This operation is carried out at room temperature. Concrete beams strengthened with glass fibre fabric are cured for 24 hours at room temperature before testing.

4.7 EXPERIMENTAL SETUP

The Deep beams with holes are tested in the loading frame of the "Structural Engineering" Laboratory of National Institute of Technology, Rourkela. The testing procedure for the all the specimen is same. First the beams are cured for a period of 28 days then its surface is cleaned with the help of sand paper to make the cracks clearly visible after testing. One point loading arrangement is used for testing of beams.

The load is transmitted through a load cell and spherical seating directly at the midpoint of the beam. The specimens placed over the two steel rollers bearing leaving 150 mm from the ends of the beam. One dial gauge is used for recording the deflection of the beam and is placed at the centre of the beam.

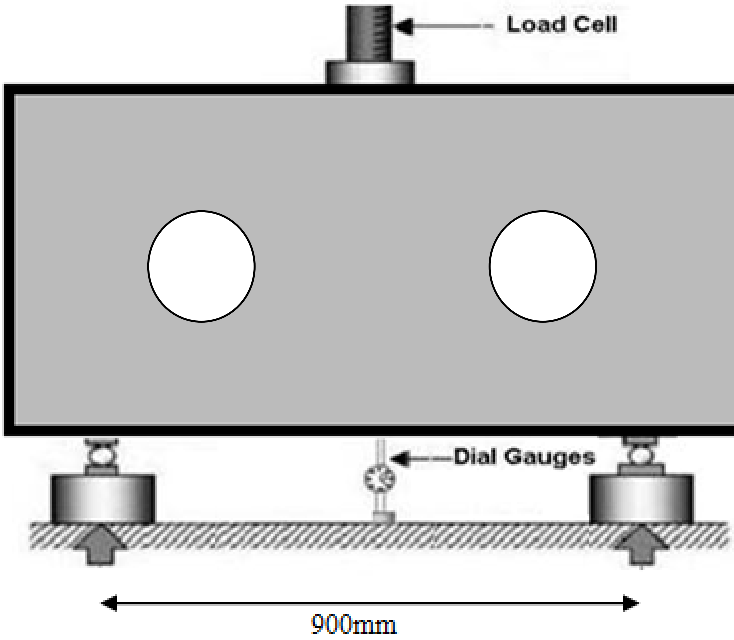


Fig.4.3 Experimental setup

4.8 FABRICATION OF GFRP PLATE

There are two basic processes for moulding: hand lay-up and spray-up. The hand lay-up process is the oldest and simplest fabrication method. The process is most common in FRP marine construction. In hand lay-up process, liquid resin is placed along with FRP against finished surface. Chemical reaction of the resin hardens the material to a strong light weight product. The resin serves as the matrix for glass fibre as concrete acts for the steel reinforcing rods.

The following constituent materials were used for fabricating plates:

1. Glass Fibre
2. Epoxy as resin
3. Hardener as diamine (catalyst)
4. Polyvinyl alcohol as a releasing agent

A plastic sheet was kept on the plywood platform and a thin film of polyvinyl alcohol was applied as a releasing agent by the use of spray gun. Laminating starts with the application of a gel coat (epoxy and hardener) deposited in the mould by brush, whose main purpose was to provide a smooth external surface and to protect fibres from direct exposure from the environment. Steel roller was applied to remove the air bubbles. Layers of reinforcement were applied and gel coat was applied by brush. Process of hand lay-up is the continuation of the above process before gel coat is hardened. Again a plastic sheet was applied by applying polyvinyl alcohol inside the sheet as releasing agent. Then a heavy flat metal rigid platform was kept top of the plate for compressing purpose. The plates were left for minimum 48 hours before transported and cut to exact shape for testing.

Plates were casted using two different glass fibres of 2 layers, 4 layers which are closely spaced and the specimen of 2 layers, 4 layers which are largely spaced and are tested.

Fig.4.4 Specimens for testing.

Fig.4.5 Experimental set up of INSTRON 1195

Fig.4.6 Failure of specimen after tensile test

Table4.2 Size of the specimens for tensile test

No. of layers	Length (cm)	Width (cm)	Thickness (cm)
2(closely spaced)	15	2.3	0.1
4(closely spaced)	15	2.3	0.25
2(largely spaced)	15	2.3	0.3

4.9 DETERMINATION OF ULTIMATE STRESS, ULTIMATE LOAD AND YOUNG'S MODULUS

The ultimate stress, ultimate load and young's modulus was determined experimentally by performing unidirectional tensile test on the specimens cut in longitudinal and transverse direction. The dimensions of the specimens are shown in Table 4.2. The specimens were cut from the plates by diamond cutter or by hex saw. After cutting by hex saw, it was polished in the polishing machine.

For measuring the young's modulus, the specimen is loaded in INSTRON 1195 universal tensile test machine to failure with a recommended rate of extension. Specimens were gripped in the upper jaw first and then gripped in the movable lower jaw. Gripping of the specimen should be proper to prevent slippage. Here, it is taken as 50 mm from each side. Initially, the stain is kept zero. The load as well as extension was recorded digitally with the help of the load cell and an extensometer respectively. From these data, stress versus stain graph was plotted, the initial slope of which gives the Young's modulus. The ultimate stress and the ultimate load were obtained at the failure of the specimen. The average value of each layer of the specimens is given in the Table 4.3.

Table 4.3 Result of the specimens

No.of layers of the specimen	Ultimate stress (MPa)	Ultimate Load (N)	Young's modulus(MPa)
2 Layers(closely spaced)	172.79	6200	6829.9
4 Layers(closely spaced)	209.09	9200	7788.5
2 Layers(largely spaced)	268.6	30890	6158
4 Layers(largely spaced)	271.48	31221	6224.02

4.10 TESTING OF BEAMS

All the five are tested one by one. Four with FRP and one without FRP which is taken as the control Beam .All of them are tested in the above arrangement. The gradual increase in load and the deformation in the strain gauge reading are taken throughout the test. The dial gauge reading shows the deformation. The load at which the first visible crack is developed is recorded as cracking load. Then the load is applied till the ultimate failure of the beam.

The deflections at the midpoint mentioned for the beams with and without GFRP are recorded with respect to increase of load and are furnished in table. The data furnished in this chapter have been interpreted and discussed in the chapter 6 to obtain a conclusion.

4.10.1 Beam No.1 (Control Beam)

Fig. 4.7 Deep Beam specimen for testing

Fig. 4.8(a) Specimen showing the crack pattern (front)

Fig. 4.8(b) Specimen showing the crack pattern (back)

Table 4.4 Deflection Values of Control Beam

Load (KN)	Deflection (mm) at L/2	Remarks
10	0.15	
20	0.23	
30	0.32	
40	0.44	
50	0.54	
60	0.69	
70	0.89	
80	1.12	
90	1.39	1st crack appeared
100	1.69	
110	1.94	
120	2.49	Ultimate load

4.10.2 Beam – 2

Double layered U- wrap GFRP (closely spaced) bonded in the clear shear span.

Fig. 4.9 U-wrap GFRP wrapped at Beam 2

Fig. 4.10 Beam 2 after testing

Fig. 4.11 Flexure crack at the midpoint of the beam

Fig. 4.12 Debonding of GFRP

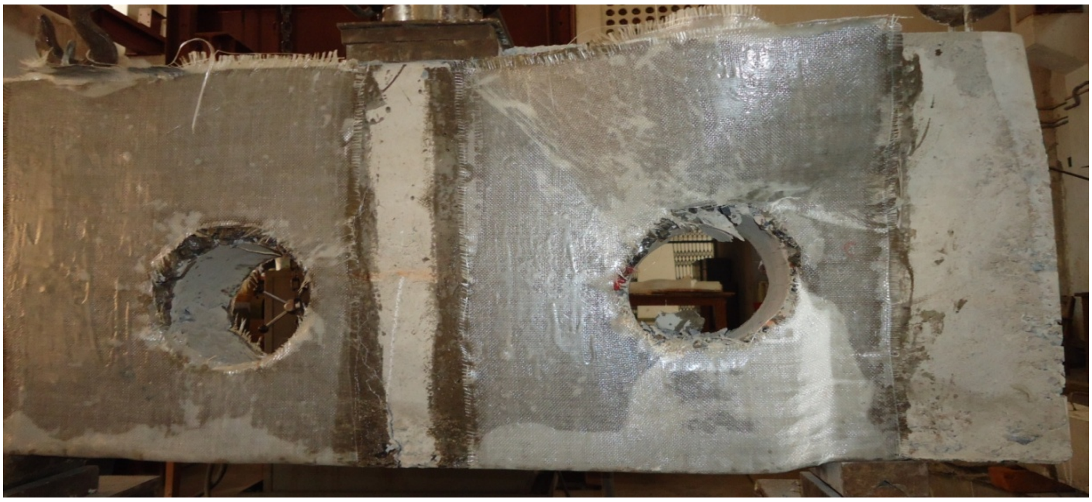


Fig. 4.13 Debonding of GFRP at 232 KN

Table 4.5 Deflection Values of Beam-2

Load (KN)	Deflection (mm) at L/2	Remarks
10	0.19	
20	0.28	
30	0.39	
40	0.49	
50	0.59	
60	0.65	
70	0.75	
80	0.86	
90	0.90	
100	1.02	
110	1.13	
120	1.24	
130	1.39	
140	1.57	
150	1.67	
160	1.80	
170	1.94	
180	2.14	
190	2.31	1^{st} crack appeared
200	2.75	
210	3.00	
220	3.10	
232		Ultimate load

4.10.3 Beam-3

Four layered U- wrap GFRP (closely spaced) bonded in the clear shear span.

Fig. 4.14 U-wrap GFRP wrapped at Beam 3

Fig. 4.15 Debonding of GFRP

Fig. 4.16 Debonding of GFRP

Fig. 4.17 Beam 3 showing both the flexural and shear cracks

Table 4.6 Deflection Values of Beam-3

Load (KN)	Deflection (mm) at L/2	Remarks
10	0.19	
20	0.29	
30	0.39	
40	0.49	
50	0.58	
60	0.64	
70	0.72	
80	0.80	
90	0.88	
100	0.94	
110	1.08	
120	1.19	
130	1.34	
140	1.51	
150	1.62	
160	1.69	
170	1.80	
180	1.93	
190	2.28	
200	2.33	1^{st} crack appeared
210	2.42	
220	2.54	
230	2.74	
240	2.92	Crack started inside the fibre
270		Ultimate load

4.10.4 Beam-4

Double layered Full-wrap GFRP (largely spaced) bonded in the clear shear span.

Fig. 4.18 Full-wrap GFRP wrapped at Beam 4

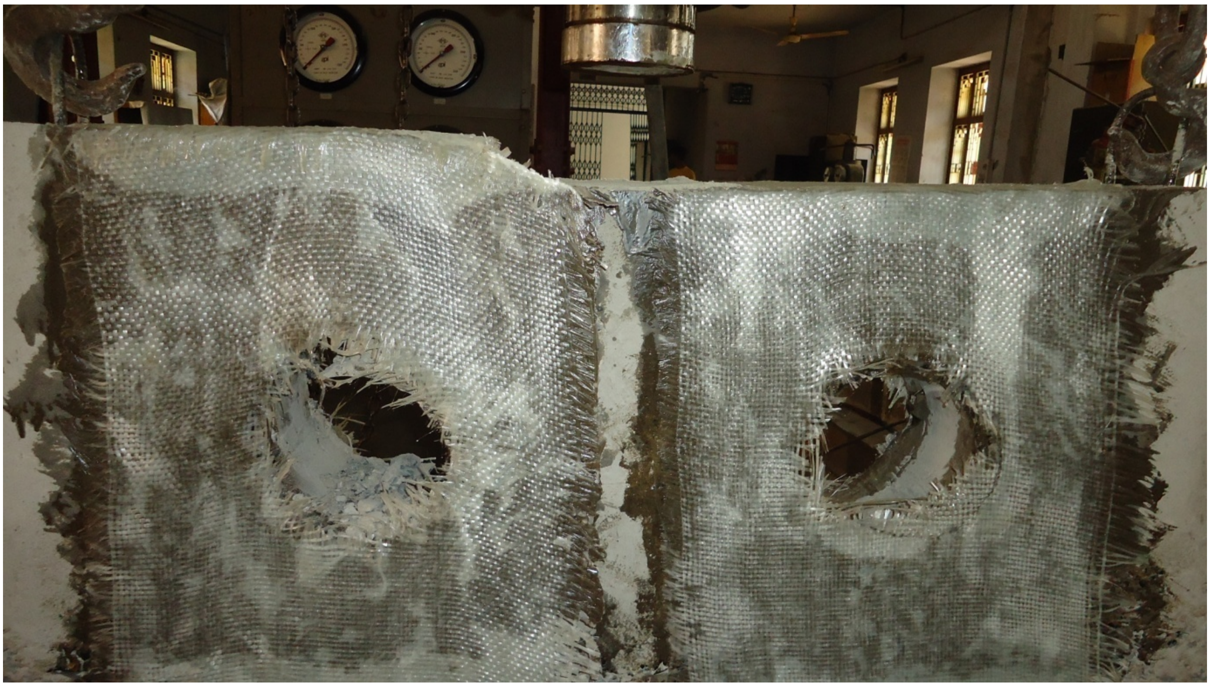


Fig. 4.19 Beam 4 after testing

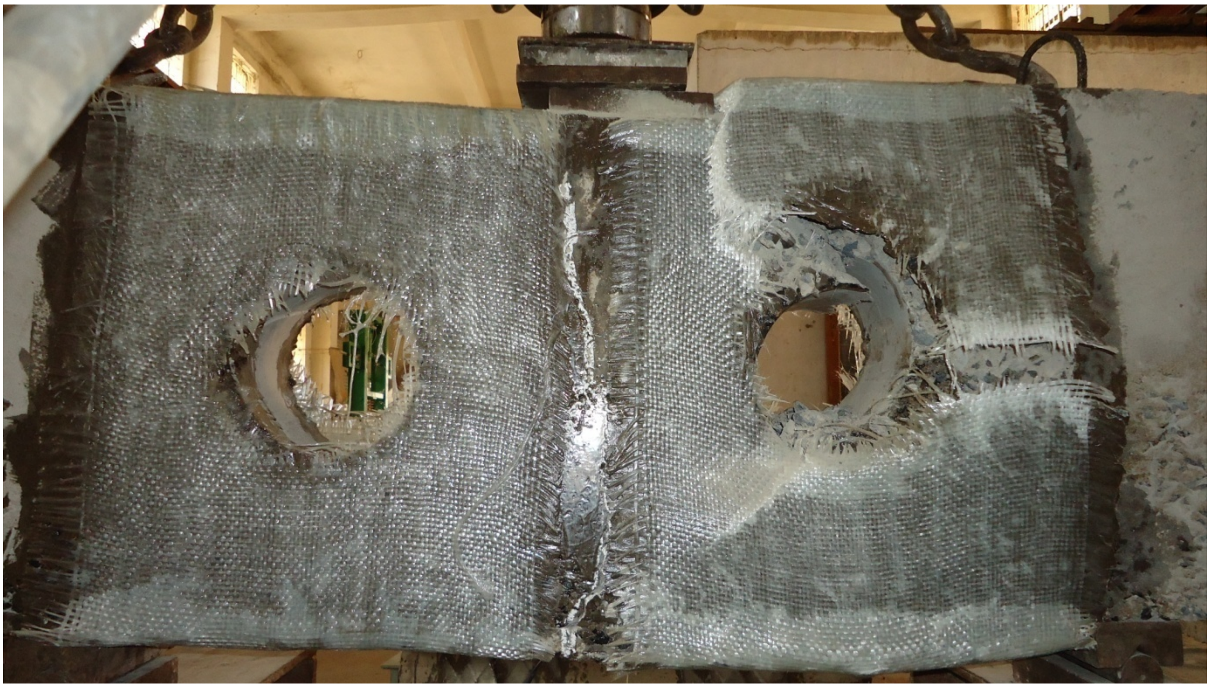


Fig. 4.20 Beam 4 showing flexural crack and rupture of GFRP

Fig. 4.21 Rupture of GFRP at the bottom of the Beam 4

Table 4.7 Deflection Values of Beam-4

Load (KN)	Deflection (mm) at L/2	Remarks
10	0.18	
20	0.24	
30	0.32	
40	0.39	
50	0.46	
60	0.52	
70	0.59	
80	0.65	
90	0.74	
100	0.85	
110	0.97	
120	1.14	
130	1.29	
140	1.46	
150	1.62	1st crack appeared
160	1.79	
170	2.07	
180	2.29	
190	2.54	
200	2.85	
202		Ultimate load

4.10.5 Beam-5

Four layered Full-wrap GFRP (largely spaced) bonded in the clear shear span.

Fig. 4.22 Full-wrap GFRP wrapped at Beam 5

Fig. 4.23 Beam 5 after testing

Fig. 4.24 Rupture of GFRP at the top of the beam 5

Fig. 4.25 Beam 5 showing Debonding of GFRP

Table 4.8 Deflection Values of Beam-5

Load (KN)	Deflection (mm) at L/2	Remarks
10	0.19	
20	0.28	
30	0.32	
40	0.40	
50	0.49	
60	0.58	
70	0.64	
80	0.70	
90	0.76	
100	0.81	
110	0.90	
120	1.21	
130	1.31	
140	1.52	1^{st} crack appeared
150	1.65	
160	1.78	
170	1.97	
180	2.03	
190	2.36	
200	2.46	
210	2.58	
232		Ultimate load

CHAPTER-5

FINITE ELEMENT ANALYSIS

5.1 INTRODUCTION

The finite element method is a numerical analysis technique for obtaining approximate solutions to a wide variety of engineering problems. ANSYS is a general purpose finite element modelling package for numerically solving a wide variety of problems which include static/dynamic structural analysis (both linear and nonlinear), heat transfer and fluid problems, as well as acoustic and electro-magnetic problems. The Deep beams with tensile reinforcement and without shear reinforcement have been analyzed using a finite element (FE) model in ANSYS. Here, a linear analysis is considered throughout the study by assuming that there is a perfect bonding between reinforcement and the steel.

5.2 FINITE ELEMENT MODELLING.

5.2.1 Reinforced Concrete.

SOLID65 is used for the 3-D modelling of solids with or without reinforcing bars (rebar). The solid is capable of cracking in tension and crushing in compression. In concrete applications, for example, the solid capability of the element may be used to model the concrete while the rebar capability is available for modelling reinforcement behaviour. Other cases for which the element is also applicable would be reinforced composites (such as fibreglass), and geological materials (such as rock). The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. Up to three different rebar specifications may be defined.

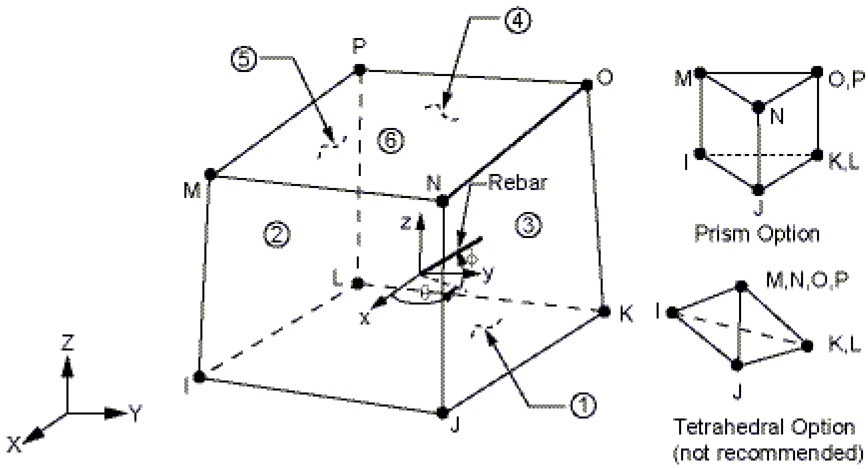


Fig. 5.1 SOLID65 element

5.2.2 Steel Reinforcement.

To model concrete reinforcing, discrete modelling is used by assuming that bonding between steel and concrete is 100 percent. BEAM188 is used as reinforcing bars, it is a quadratic beam element in 3-D. BEAM188 has six degrees of freedom at each node. These include translations in the x, y, and z directions and rotations about the x, y, and z directions. This element is well-suited for linear, large rotation, and/or large strain nonlinear applications.

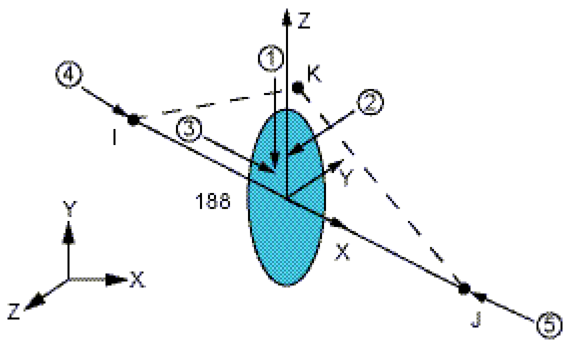


Fig. 5.2 BEAM188 element

5.2.3 Steel Plates.

To model supports and under the load steel plate is used, which SOLID 45 is used, it is used for the 3-D modelling of solid structures. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

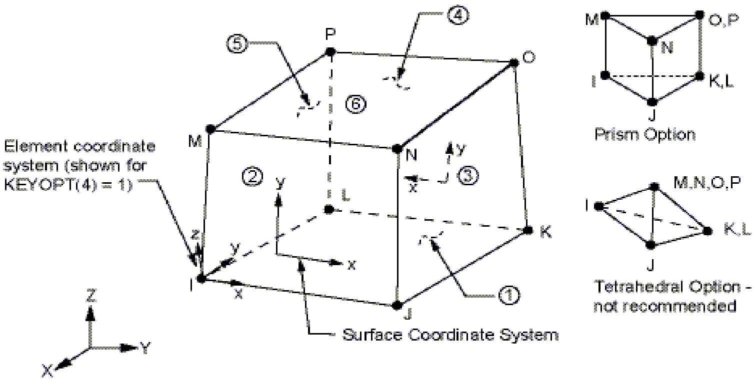


Fig. 5.3 SOLID45 element.

5.2.4 Laminates.

To model laminated composites SHELL 91 is used. It may be used for layered applications of a structural shell model or for modelling thick sandwich structures. Up to 100 different layers are permitted for applications with the sandwich option turned off. When building a model using an element with *fewer* than three layers, SHELL 91 is more efficient than SHELL 99.

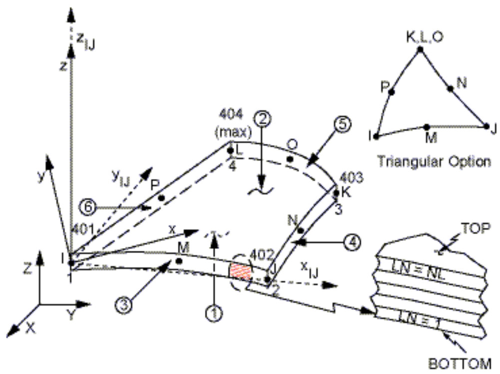


Fig. 5.4 SHELL91 element.

5.3 MATERIAL PROPERTIES.

Linear analysis is considered for modelling of deep beam with openings, Table 5.1 summarizes the material linear properties and elements used in the modelling.

Table 5.1 Material properties and elements used in the modelling.

Materials	Density (kg/m3)	Elastic Modulus (MPa)	Poison's ratio	Fc28 (MPa)	Fy (MPa)	Element Used
Concrete	2400	19364	0.17	15	-	SOLID65
Reinforcing Steel	7850	210000	0.27	-	415	BEAM188
Steel Plate	7850	210000	0.27	-	415	SOLID45

5.4 GEOMETRY AND LOADING CONDITIONS.

Simply supported beam is considered having and overall length of 1200 mm with effective length of 900 mm. Size of the beam is 150 x 460 mm. Figure 5.5 shows the control beam with boundary conditions used in the analysis. Single point loading is applied at the midpoint of the beam. To get the accuracy of results mesh size considered as 25 mm as edge length.

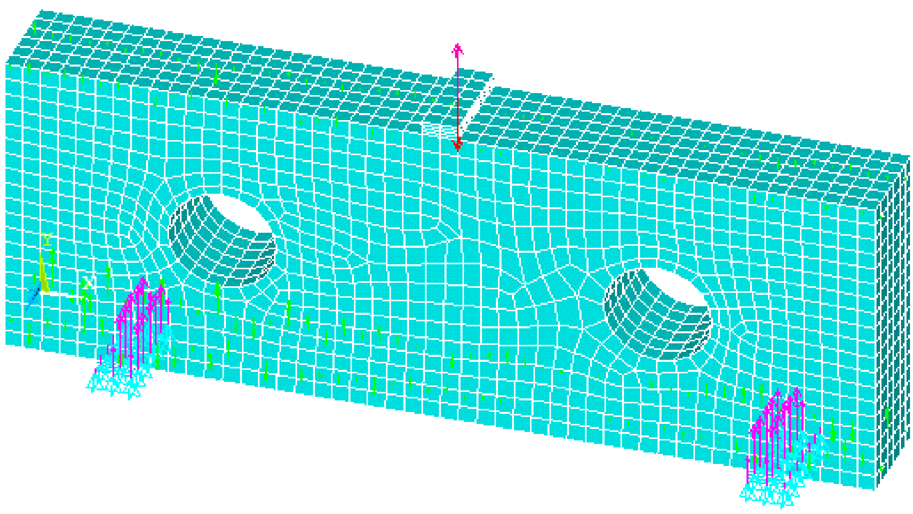


Fig. 5.5 Deep beam model in ANSYS.

High-Yield Strength Deformed bars of 12 mm and 8 mm diameter are used for the longitudinal reinforcement and 6 mm diameter bars are used as stirrups. The tension reinforcement consists of 2 no’s 12 mm diameter HYSD bars. Two bars of 8 mm of HYSD bars are also provided as hang up bars .The detailing of reinforcement of the beam is shown in figure 5.6 and figure 5.7 shows the deep beam model with FRP.

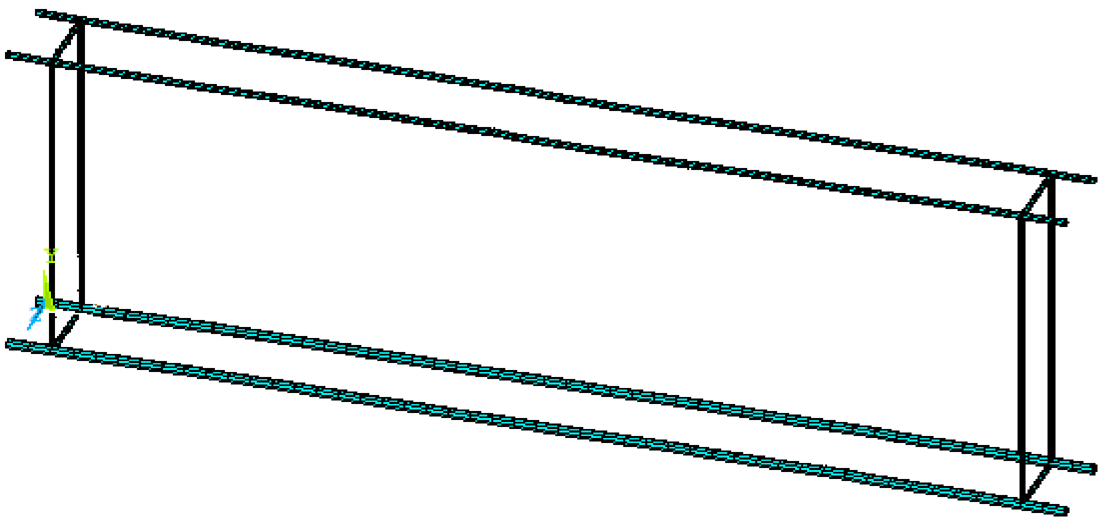


Fig. 5.6 Reinforcement model in ANSYS.

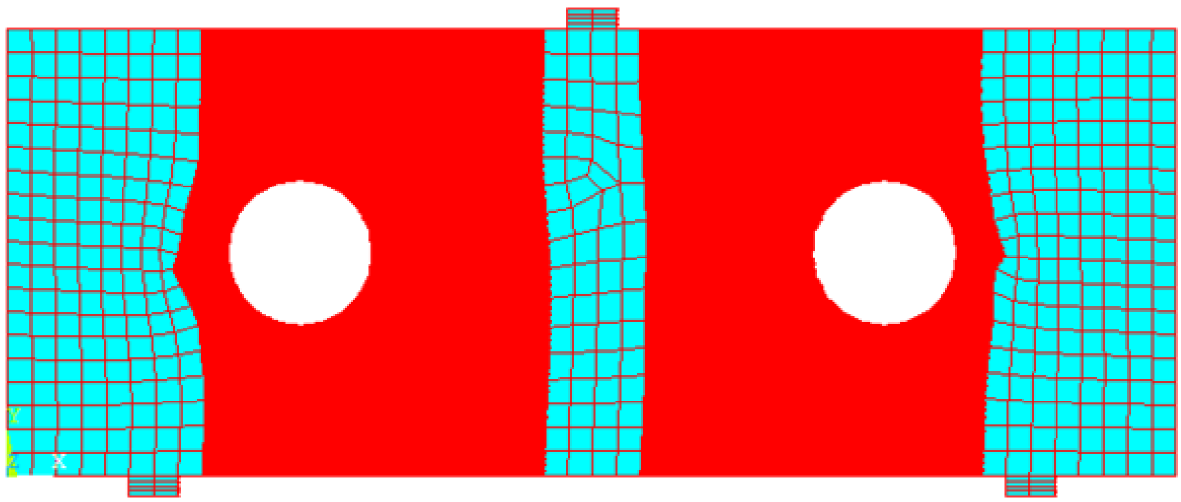


Fig. 5.7 Deep beam model with FRP in ANSYS.

CHAPTER-6

RESULTS AND DISCUSSIONS

6.1 INTRODUCTION

In this chapter the experimental results of all the beams with different types of layering of GFRP are interpreted. Their behavior throughout the test is described using recorded data on deflection behavior and the ultimate load carrying capacity. The crack patterns and the mode of failure of each beam are also described in this chapter. All the beams are tested for their ultimate strengths.Beams-1 is taken as the control beam. It is observed that the control beam had less load carrying capacity when compared to that of the externally strengthened beams using GFRP sheets.

All the beams except the control beam are strengthened at clear shear span with GFRP sheets in different patterns.Beam-2 is strengthened using double layer u-wrap of GFRP(closely spaced) and similarly beam -3 is strengthened using four layer u-wrap of GFRP(closely spaced) sheets. Beam-4 is strengthened using double layer full wrap of GFRP(largely spaced) and beam-5 is strengthened using four layer full wrap of GFRP(largely spaced) sheets.

6.2 FAILURE MODES

The following failure modes are investigated for a GFRP strengthened section:

- Debonding of the FRP from the concrete substrate (FRP debonding).
- Rupture of FRP sheets.
- Shear failure.
- Flexure failure.

A number of failure modes have been observed in the experimental study of RC deep beams with openings strengthened in shear by GFRPs. These include shear failure, shear failure due to GFRP rupture and crushing of concrete at the top and failure in flexure. Rupture of the FRP laminate is assumed to occur if the strain in the FRP reaches its design rupture strain before the concrete reaches its maximum usable strain. GFRP debonding can occur if the force in the FRP cannot be sustained by the substrate. In order to prevent debonding of the GFRP laminate, a limitation should be placed on the strain level developed in the laminate.

The GFRP strengthened beam and the control beams are tested to find out their ultimate load carrying capacity. It is found that all the beams failed in shear and some in flexure. The beams which failed in shear showed frame type failure which occurs by the formation of two independent diagonal cracks one in each member bridging the two solid beam segments leads to failure.Beam-2 and beam-3 failed due to debonding of GFRP sheet followed by shear cracks and a flexure crack at the midpoint of the beam. Beam-4 failed due to rupture of GFRP sheets followed by shear cracks and a flexure crack at the midpoint of the beam.Beam-5 failed due to rupture and debonding of GFRP sheets followed by shear cracks and a flexure crack at the midpoint of the beam.

6.3 LOAD DEFLECTION ANALYSIS

Here the deflection of each beam at different positions is analyzed. Linear analysis of beams is done in ANSYS and mid-span deflections of each beam are compared with ANSYS model. Also the load deflection behavior is compared between different wrapping schemes having the same reinforcement. It is noted that the behavior of the shear deficient beams when bonded with GFRP sheets are better than the control beams. The use of GFRP sheet had effect in delaying the growth of crack formation.

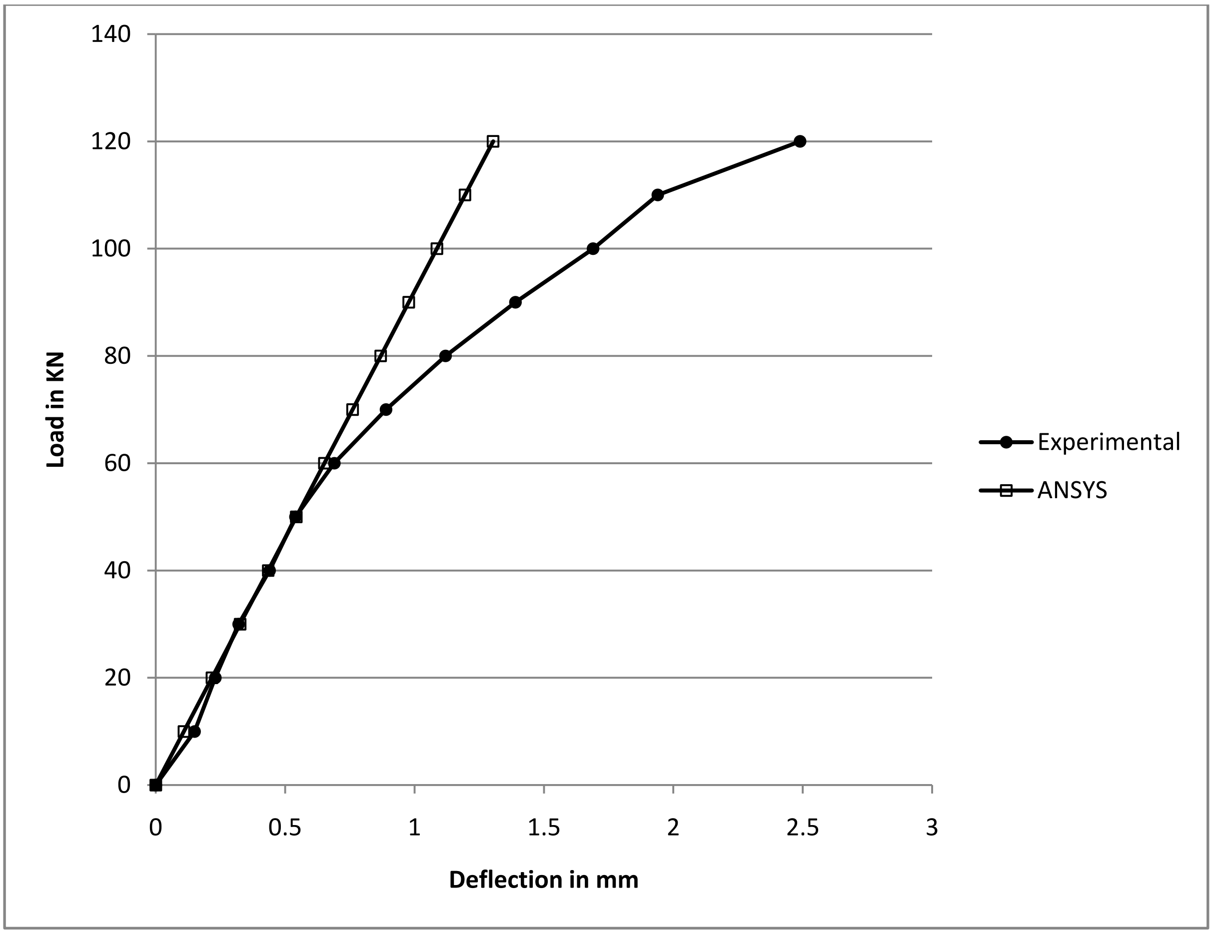


Fig. 6.1 Load vs. Deflection curve for control Beam-1.

Beam 1 is taken as the control beam which is weak in shear. In Beam1 no strengthening is done. Three point loading is applied on the beam and at the each increment of the load, deflection values at L/2 are taken with the help of dial gauge. Using this load and deflection data, load vs. deflection curve is plotted. At the load of 90 KN first crack appeared. Later with the increase in loading values the crack propagated further. The Beam1 failed completely in shear showing frame type failure. Since liner FEM model is being adopted, the deflections obtained using ANSYS are in good agreement for lower range of load values when compared with experimental results.

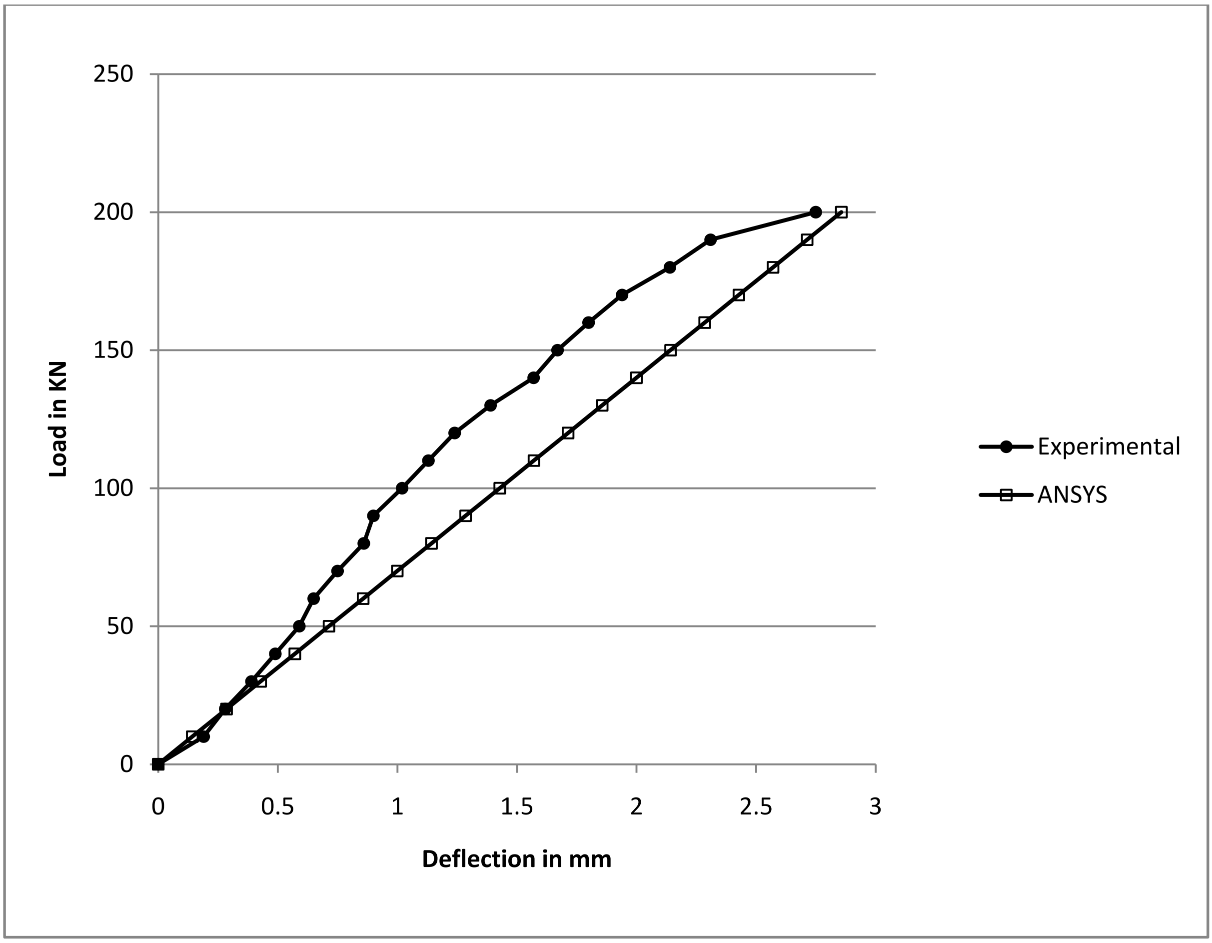


Fig. 6.2 Load vs. Deflection curve for Beam-2.

Beam-2 is strengthened using double layer u-wrap of GFRP(closely spaced).Three point loading is applied on the beam and at the each increment of the load, deflection values at L/2 are taken with the help of dial gauge. Using this load and deflection data, load vs. deflection curve is plotted. At the load of 190 KN initial hairline cracks appeared. Later with the increase in loading values the crack propagated further. Beam-2 failed due to debonding of GFRP sheet followed by shear cracks and a flexure crack at the midpoint of the beam. Since liner FEM model is being adopted, the deflections obtained using ANSYS are in good agreement for lower range of load values when compared with experimental results.

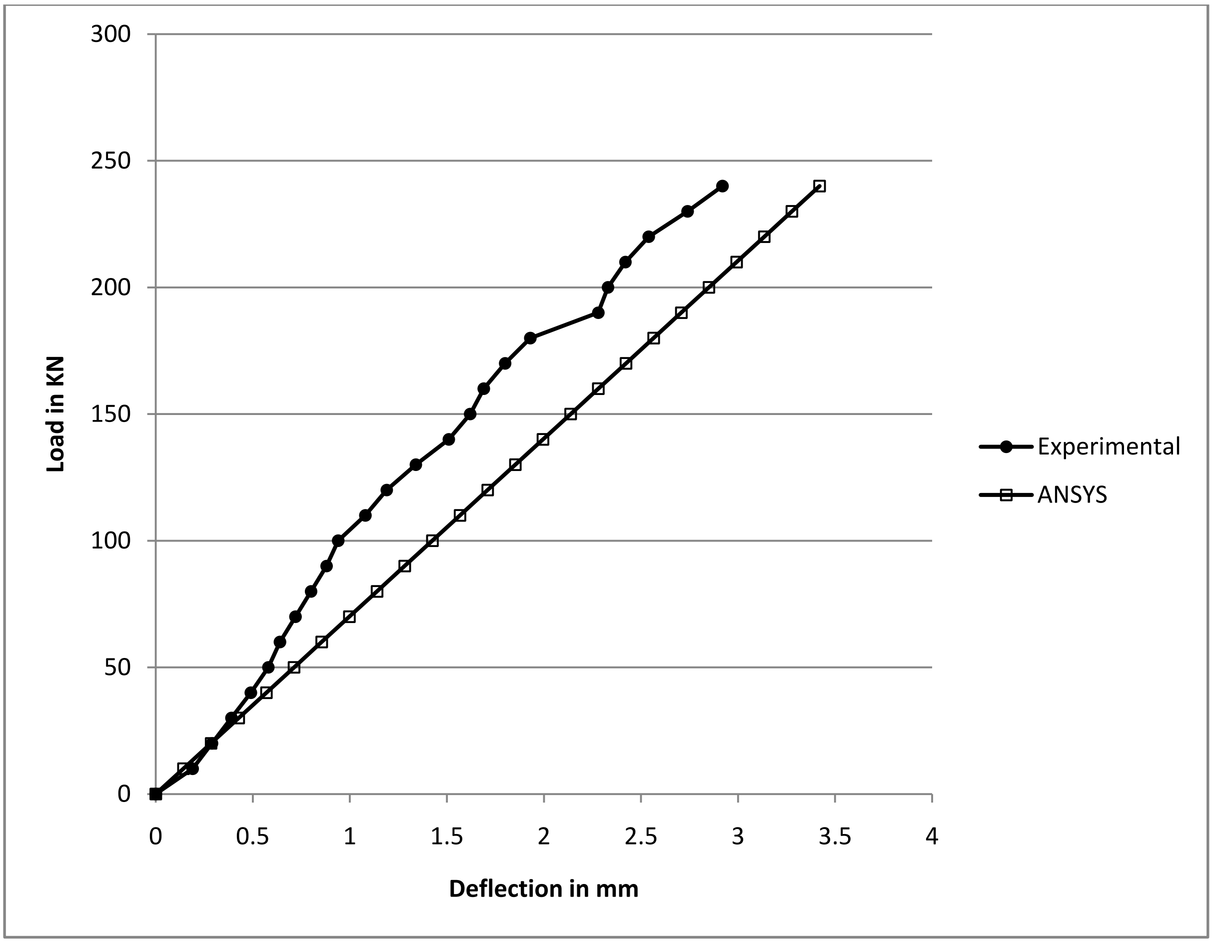


Fig. 6.3 Load vs. Deflection curve for Beam-3.

Beam-3 is strengthened using four layer u-wrap of GFRP(closely spaced).Three point loading is applied on the beam and at the each increment of the load, deflection values at L/2 are taken with the help of dial gauge. Using this load and deflection data, load vs. deflection curve is plotted. At the load of 200 KN initial hairline cracks appeared. Later with the increase in loading values the crack propagated further. Beam-3 also failed due to debonding of GFRP sheet followed by shear cracks and a flexure crack at the midpoint of the beam. Since liner FEM model is being adopted, the deflections obtained using ANSYS are in good agreement for lower range of load values when compared with experimental results.

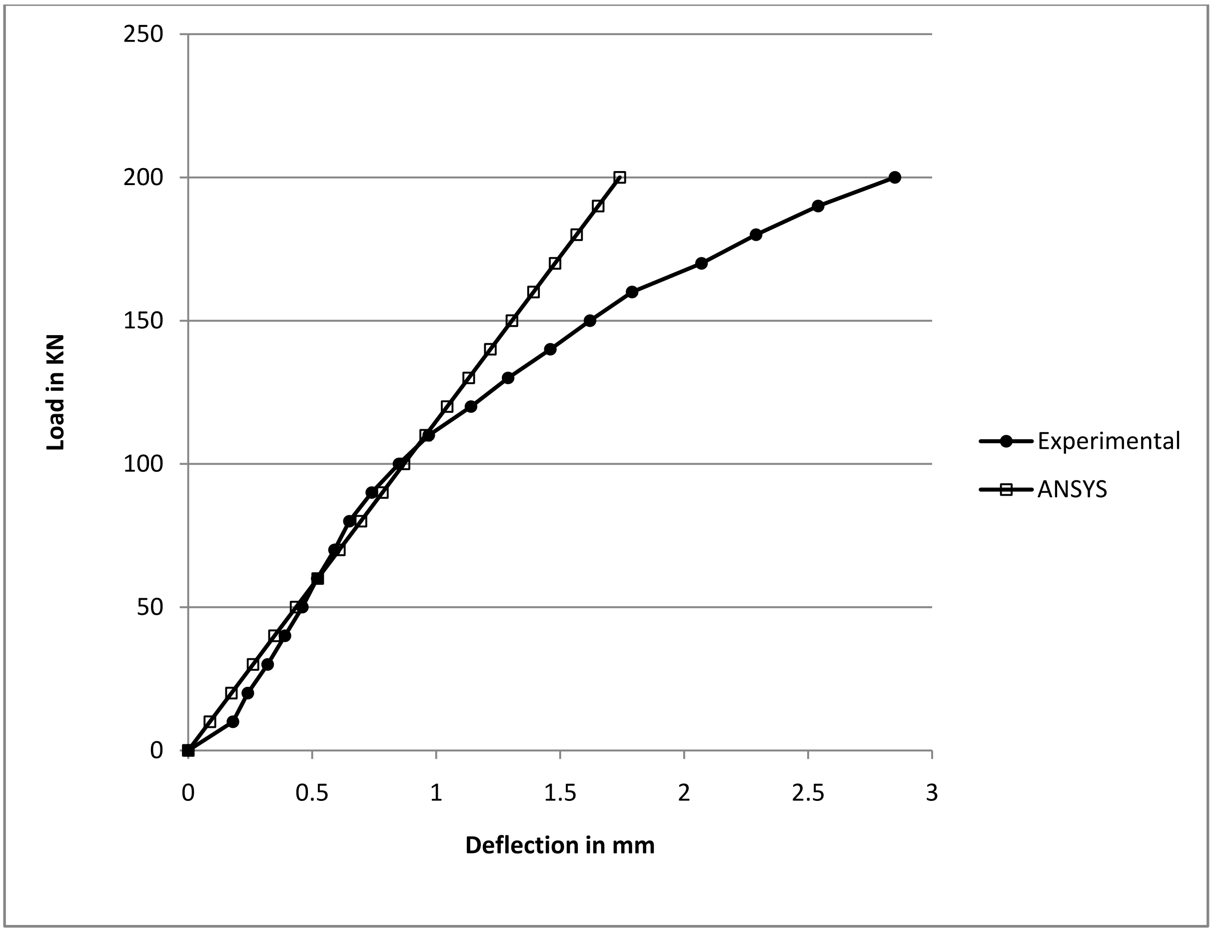


Fig. 6.4 Load vs. Deflection curve for Beam-4.

Beam-4 is strengthened using double layer full wrap of GFRP (largely spaced). Three point loading is applied on the beam and at the each increment of the load, deflection values at L/2 are taken with the help of dial gauge. Using this load and deflection data, load vs. deflection curve is plotted. At the load of 150 KN initial hairline cracks appeared. Later with the increase in loading values the crack propagated further.Beam-4 failed due to rupture of GFRP sheets followed by shear cracks and a flexure crack at the midpoint of the beam. Since liner FEM model is being adopted, the deflections obtained using ANSYS are in good agreement for lower range of load values when compared with experimental results.

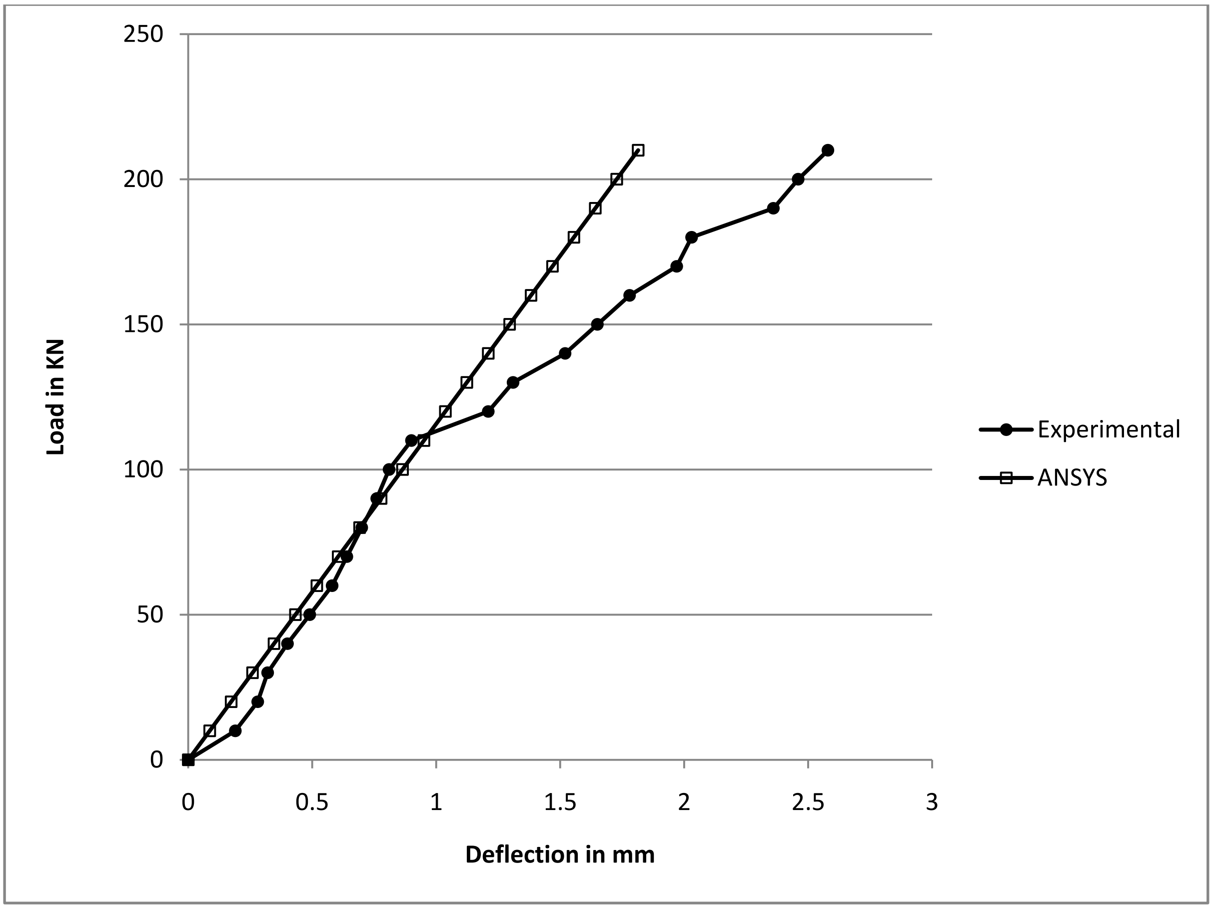


Fig. 6.5 Load vs. Deflection curve for Beam-5.

Beam-5 is strengthened using four layer full wrap of GFRP (largely spaced) sheets. Three point loading is applied on the beam and at the each increment of the load, deflection values at L/2 are taken with the help of dial gauge. Using this load and deflection data, load vs. deflection curve is plotted. At the load of 140 KN initial hairline cracks appeared. Later with the increase in loading values the crack propagated further.Beam-5 failed due to rupture and debonding of GFRP sheets followed by shear cracks and a flexure crack at the midpoint of the beam. Since liner FEM model is being adopted, the deflections obtained using ANSYS are in good agreement for lower range of load values when compared with experimental results.

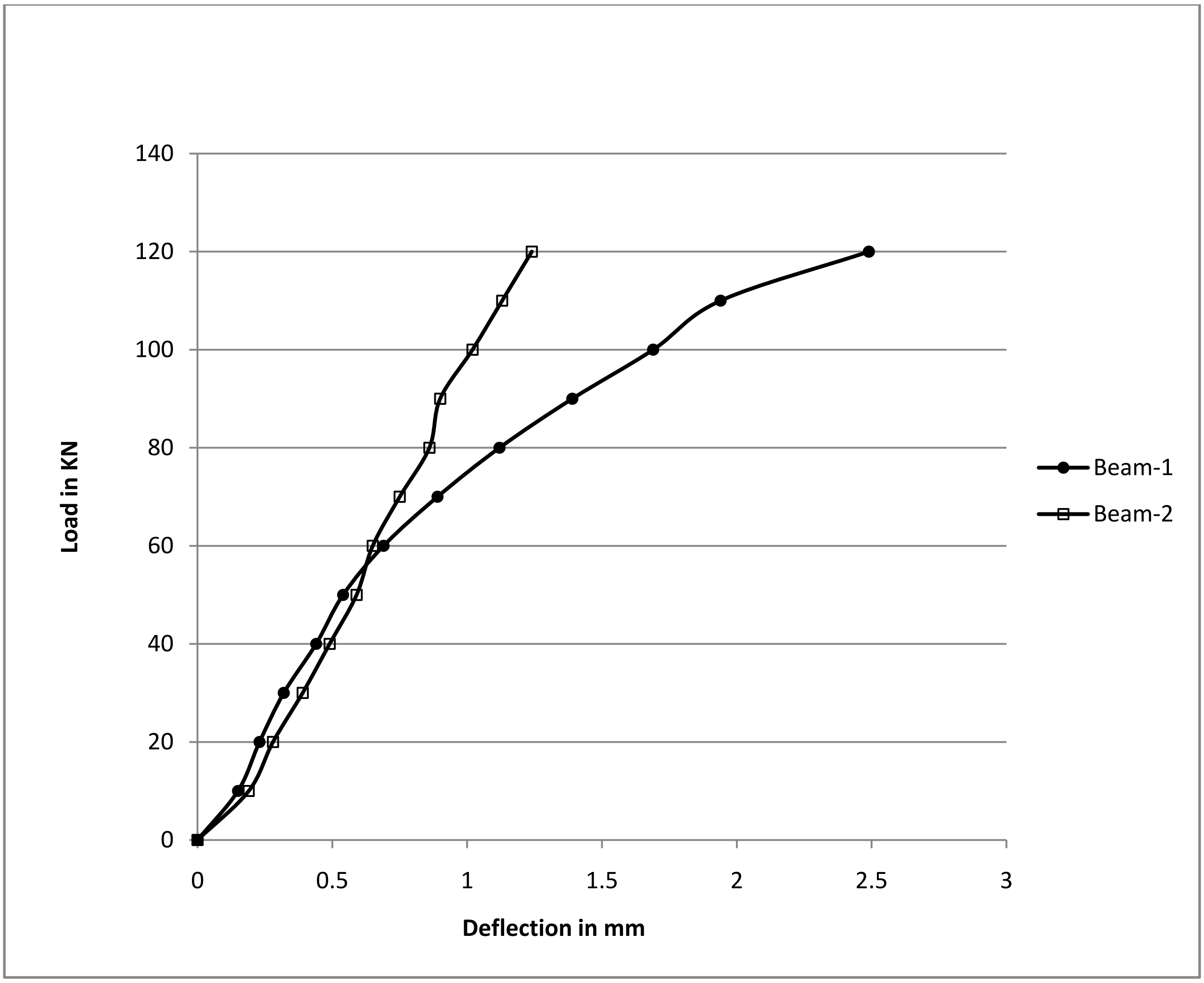


Fig. 6.6 Load vs. Deflection curve for Beam-1 and Beam-2.

From this figure it is observed that deflection in case of Beam-2 which has been strengthened in the clear shear span with GFRP (closely spaced) is controlled to a certain extent with respect to the control Beam 1.And the ultimate load has also increased to a certain percentage which has been illustrated in the figure 6.13.

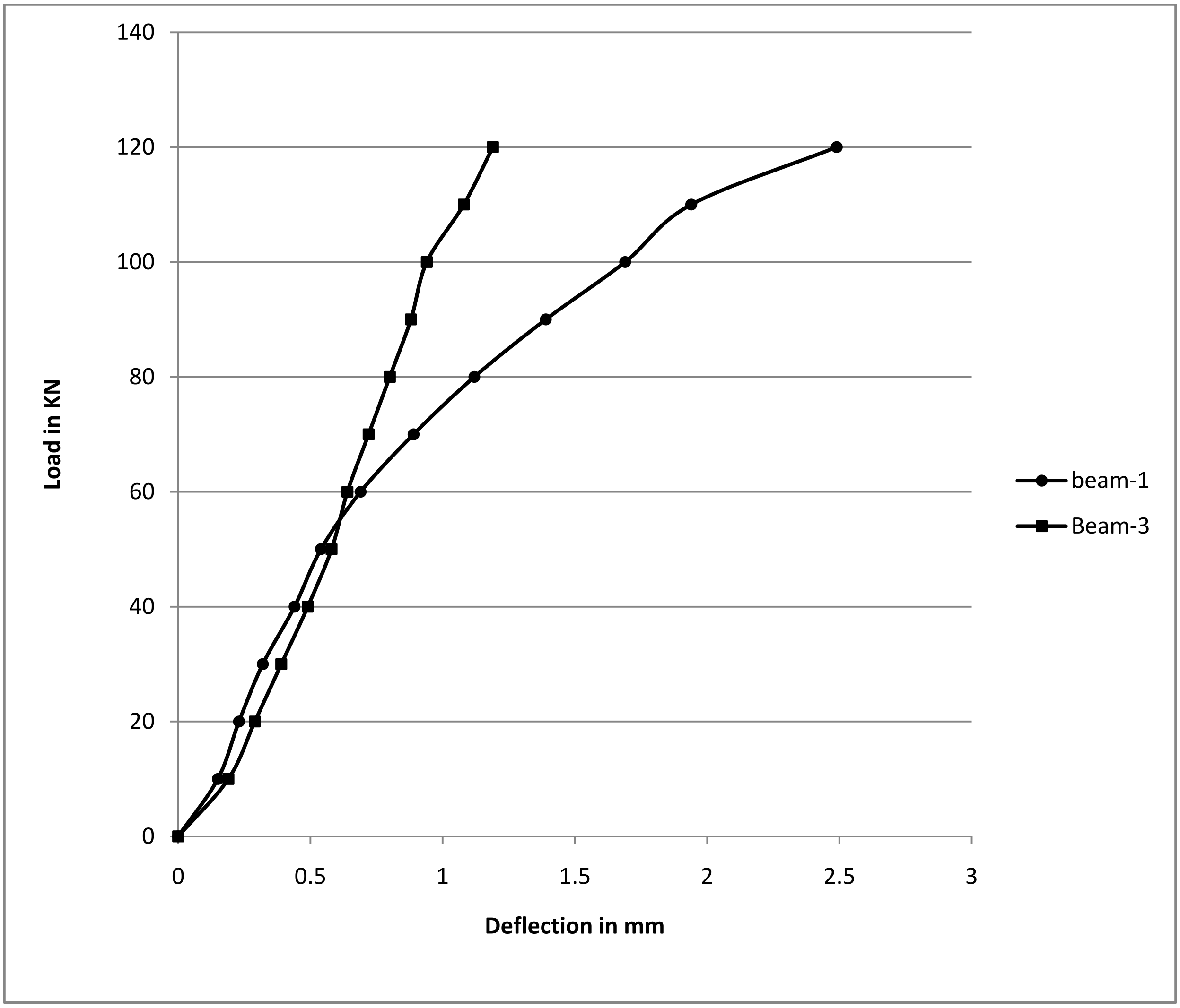


Fig. 6.7 Load vs. Deflection curve for Beam-1 and Beam-3.

From this figure it is observed that deflection in case of Beam-3 which has been strengthened in the clear shear span with GFRP (closely spaced) is controlled to a certain extent with respect to the control Beam 1.And the ultimate load has also increased to a certain percentage which has been illustrated in the figure 6.13.

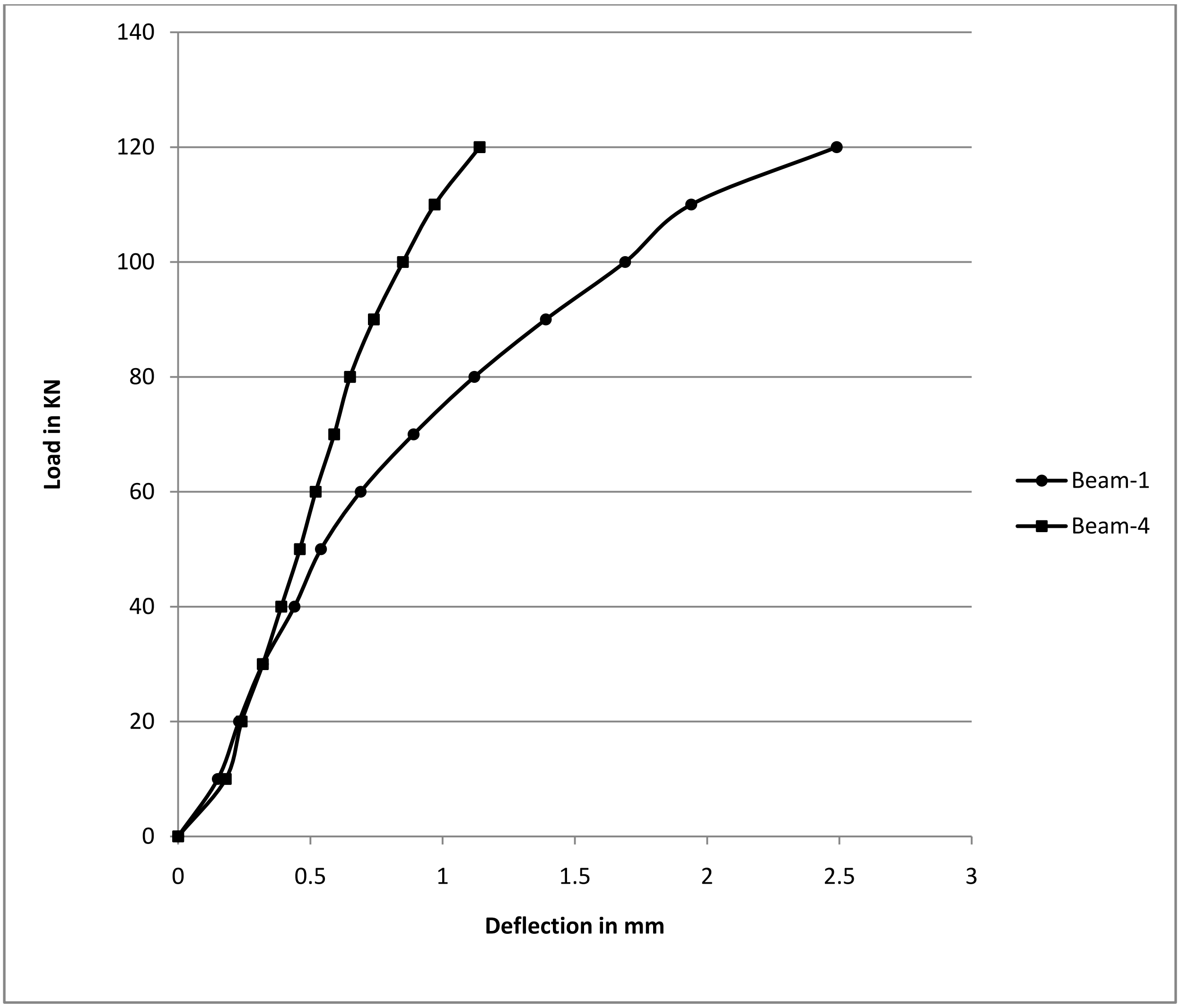


Fig. 6.8 Load vs. Deflection curve for Beam-1 and Beam-4.

From this figure it is observed that deflection in case of Beam-4 which has been strengthened in the clear shear span with GFRP (largely spaced) is controlled to a certain extent with respect to the control Beam 1.And the ultimate load has also increased to a certain percentage which has been illustrated in the figure 6.13.

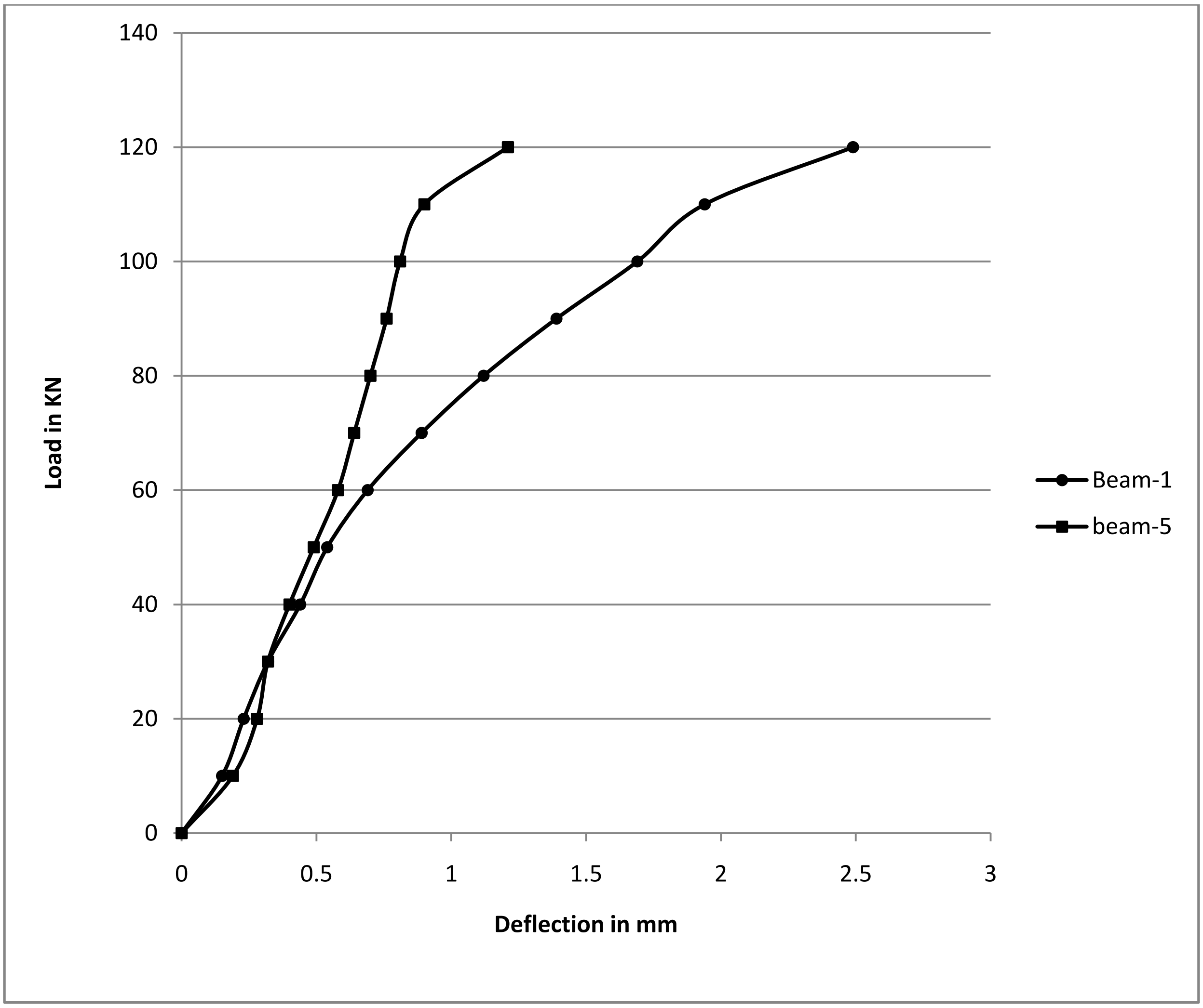


Fig. 6.9 Load vs. Deflection curve for Beam-1 and Beam-5.

From this figure it is observed that deflection in case of Beam-5 which has been strengthened in the clear shear span with GFRP (largely spaced) is controlled to a certain extent with respect to the control Beam 1.And the ultimate load has also increased to a certain percentage which has been illustrated in the figure 6.13.

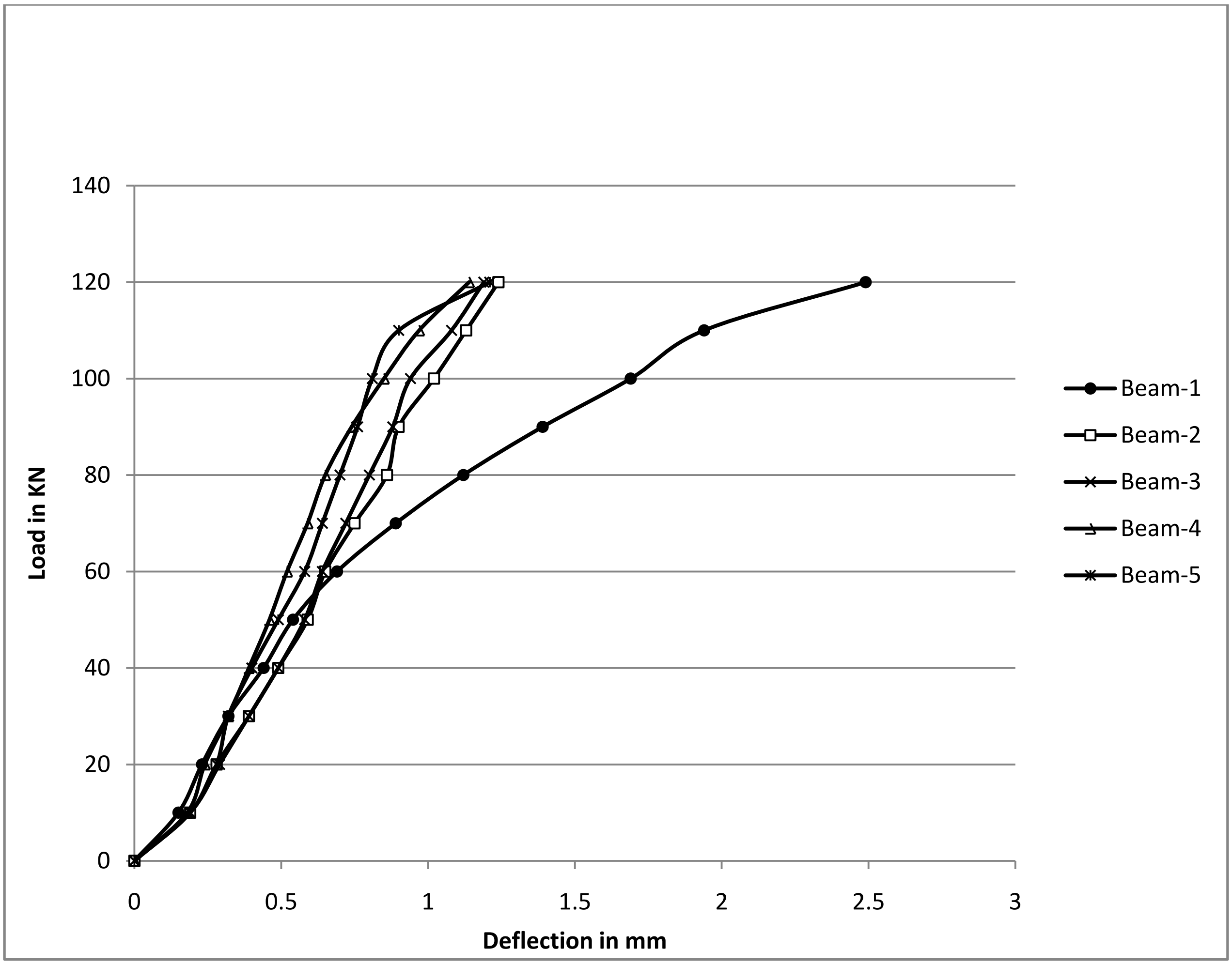


Fig. 6.10 Load vs. Deflection curve for all the beams.

Here all the beams are compared with respect to their deflection and load data. And it can be interpreted that all the beams which are strengthened, shows less deflection when compared to the control beam. Among all the strengthened beams, beam-4 which is strengthened using double layer full wrap GFRP (largely spaced) sheets shows the minimum deflection.

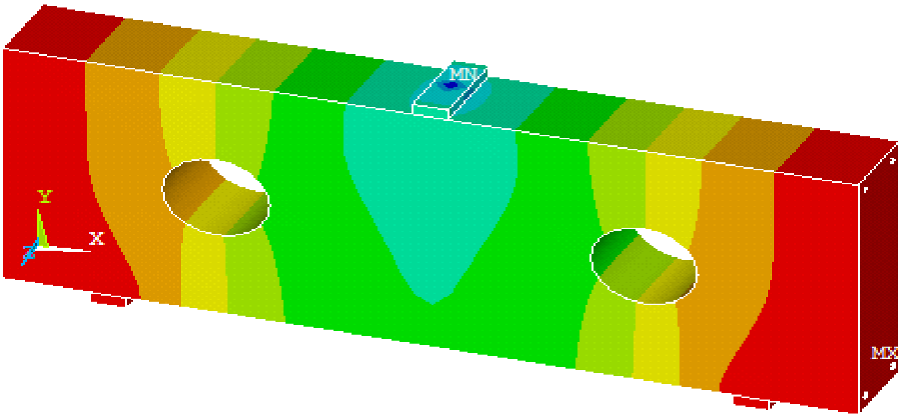


Fig. 6.11 Generalized deflection plot of deep beam model in ANSYS

6.4 ULTIMATE LOAD CARRYING CAPACITY

The load carrying capacity of the control beam and the strengthened beams are plotted below.

It is observed that beam 3 is having the maximum load carrying capacity.

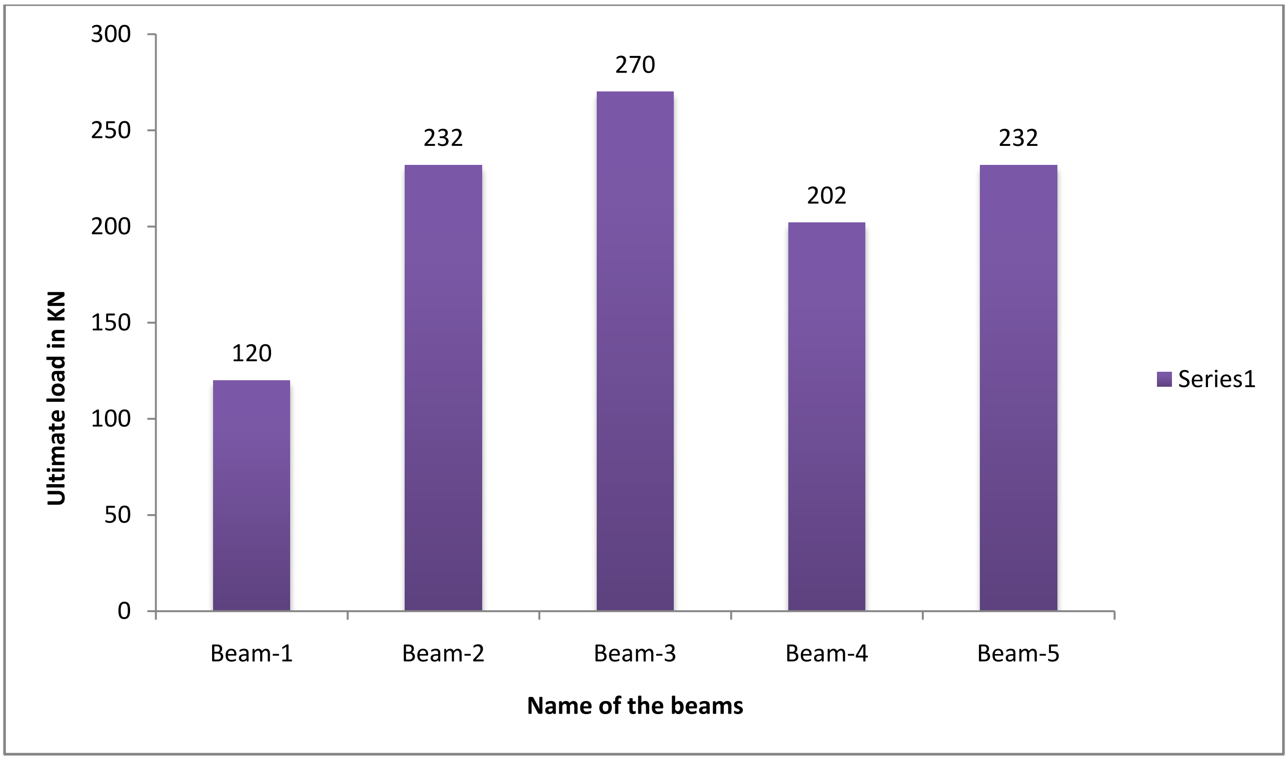


Fig. 6.12 Ultimate load carrying capacity.

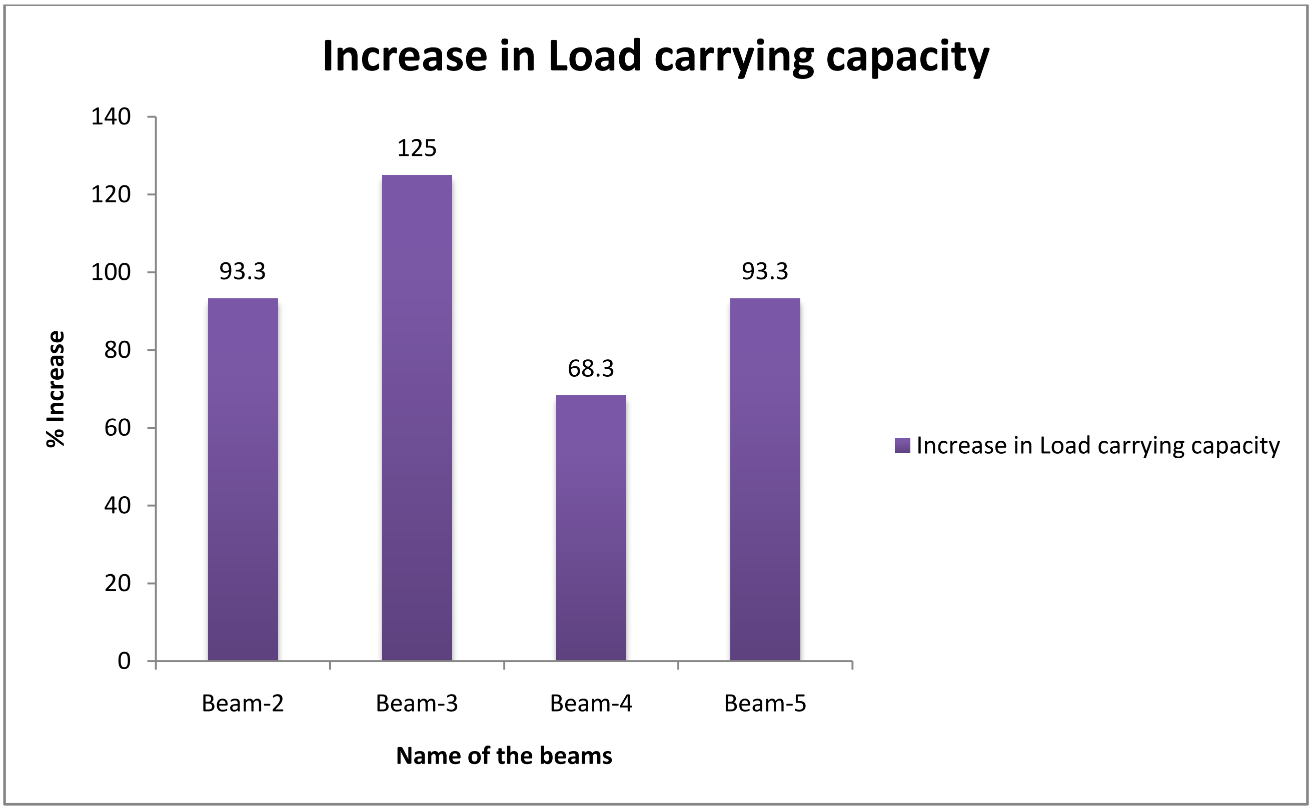


Fig. 6.13 Percentage increase in ultimate carrying capacity w.r.t. Control Beam.

From the above figure we can observe the amount of increase in the strength for each strengthened beam with respect to the Control Beam.

CHAPTER-7

CONCLUSIONS

7.1 CONCLUSIONS

The present experimental study is done on the shearbehavior of reinforced concrete deep beams containing openings strengthened by GFRP sheets. Five reinforced concrete (RC) deep beams containing openings weak in shear having same reinforcement detailing are casted and tested under three point loading. From the calculated strength values, the following conclusions are drawn:

1. The ultimate load carrying capacity of all the strengthen beams is higher when compared to the control Beam.
2. Initial shear cracks appear at higher loads in case of strengthened beams.
3. The load carrying capacity of the strengthened beam 3 which was strengthened using four layer u-wrap GFRP (closely spaced) was found to be higher when compared to beam 2 which was strengthened using double layer u-wrap GFRP(closely spaced).
4. The load carrying capacity of the strengthened beam 5 which was strengthened using four layer full-wrap GFRP (largely spaced) was found to be higher when compared to beam 4 which was strengthened using double layer full-wrap GFRP(largely spaced).
5. GFRP which is closely spaced showed better load carrying capacity when compared to GFRP which is largely spaced.
6. In lower range of load values the deflection obtained using ANSYS models are in good agreement with the experimental results. For higher load values there is a deviation with the experimental results because linear FEM has been adopted in ANSYS modelling.

7.2 SCOPE OF THE FUTURE WORK

The following areas are considered for future research

- Strengthening of deep beams containing openings with different type of FRP (like carbon fibre reinforced polymer).
- Studying the shear behaviour of deep beams with openings by varying the opening locations.
- Debonding of FRP can be prevented by anchoring the beams using steel plates.

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